Review

Elite performance in para-cycling: A scoping review

Albert Smit[1,2*], Ina Janssen[3], Florentina J. Hettinga[4], Jos J. de Koning[1], Mathijs J. Hofmijster[1] and Thomas W. J. Janssen[1,5,6]

Received: 16th July 2022; Accepted: 29th November 2023; Published: 10th May 2024

Abstract: Elite para-cycling needs an overview of relevant and valid research to better understand and improve performance and to develop the sport, using evidence-based decision making. The aim of this scoping review was to 1) provide a research overview of performance and performance determining factors in elite para-cycling to aid coaches and elite athletes, and 2) highlight the gaps in the literature. Four databases (PubMed, SportDiscus, Scopus and MEDLINE) were systematically searched for studies on para-cycling performance and performance factors and 68 relevant studies were identified. Using a conceptual framework based on a power balance model, most studies were categorized as Athlete and Interface focused, while fewer studies focused on Equipment, External conditions, or Impairment. We found several practical matters regarding training, bike fitting, aerodynamics, and prosthetics design to help coaches and elite athletes to improve performance. However, more research is needed in all categories to improve performance and develop the sport. International collaboration among coaches, researchers, and governing bodies is vital to gain valuable research data.

Keywords: bicycle; handcycle; Paralympic; power balance model; tandem; tricycle

Introduction

Paralympic cycling, or para-cycling, is a sport for cyclists with a physical impairment and consists of four divisions: Cycle, Handcycle, Tandem and Tricycle (Union Cycliste Internationale, 2020). Individuals are allocated to a division based on their impairment and the severity of the impairment. With fifty-one medal events at the Tokyo 2020 Summer Paralympic Games, para-cycling has become an increasingly competitive sport. This increased competitiveness demands increased scientific support for coaches and athletes to improve performance, but also to decrease the number of injuries, and improve the classification process.

To explore performance determining factors in cycling, a power balance model (Van Ingen Schenau & Cavanagh, 1990) can be used, which incorporates power production, power dissipation, and change in kinetic energy. Several studies used power balance models in different sports to understand and improve performance (De Koning et al., 1999; Groen et al., 2010; Hettinga et al., 2012; Hofmijster et al., 2007). As the goal of the elite para-cyclist is to achieve the highest average race velocity possible, the power balance model can be used to identify factors that can be optimized to improve performance. These performance determining factors can be internal, related to power production, or external, related to power dissipation (Jeukendrup & Martin, 2001). Performance determining factors can also be related to the interface between the athlete and the bicycle or tricycle used by the athlete (Van Der Woude et al., 2001), or to the impairments of the athletes.

Several reviews on cyclists without disabilities (e.g., Faria et al. (2005a, 2005b); Jeukendrup and Martin (2001); Phillips and Hopkins (2020)) have addressed different factors related to improvements in elite cycling performance. However, due to individual's impairments, elite para-cyclists tend to have different physiological properties and training abilities, and are positioned differently on the bicycle, compared to their counterparts without disabilities. They may, therefore, have different requirements for optimization of performance compared to elite cyclists without disabilities. Earlier work on Paralympic sports performance indicated the need for more specific research on elite athletes with a disability (Bachar & Douer, 2022; Keogh, 2011; Morrien et al., 2017; Perret, 2017). However, most para-cycling specific studies focused on rehabilitation, increasing mobility, or recreational sports (see Dyer (2016) for a recent review on cycling with a prosthesis and (Kraaijenbrink et al., 2021; Nevin et al., 2022; Stephenson et al., 2021) for recent reviews on handcycling), and not on performance enhancement of the elite para-cyclist. Furthermore, the validity of some of those studies has been questioned (Kraaijenbrink et al., 2021). Therefore, many studies on para-cycling have limited relevance for elite para-cycling. To date, a clear overview of relevant para-cycling studies indicating practical implications and identifying the gaps in research, is lacking.

The aim of this scoping review therefore is to provide coaches and elite para-athletes with practical advice to understand and improve para-cycling performance, and to help improve the development of the sport by addressing available knowledge and knowledge gaps.

Materials and Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines (Tricco et al., 2018) were used to examine the literature on performance characteristics in para-cycling. As a basis for eligibility, the article had to 1) have original empirical data, 2) be published in peer-reviewed literature in English language, 3) focus on at least one of the four divisions of para-cycling, and 4) focus on elite or world-class para-cycling performance characteristics, describing performance, physiological, biomechanical, or other traits, or, 5) focus on performance enhancements that could have a direct impact on elite para-cycling performance, meaning that the enhancement should be able to affect the performance of a para-cyclist when implemented (relevance). All articles that met the eligibility criteria were further screened for the following exclusion criteria: 1) articles with no association to cycling, 2) non-original articles, 3) articles including children or adolescents (less than 16 years old), 4) methodological studies (e.g., studies on validity and reliability of test protocols or instruments), and 5) conference abstracts of which the data were also part of a full text journal article to avoid duplicity.

Four databases were consulted in the search: PubMed, SportDiscus, Scopus and MEDLINE. Using the electronic search strategy stated below, these databases were searched for publications up to September 2023. Results were checked for duplicates and imported in Endnote (X9, Clarivate Analytics, New York, USA). Google Scholar was used as a secondary source to identify any missing articles and to consider any citations made by already identified literature.

The electronic search strategy included a general set of keywords was generated, e.g., "para-cycling", "handcycle", "amputation AND cycling", "tandem AND cycling", or "tricycling", each with different variants of writing (e.g., "tricycling" OR "tricycle" OR "tribike" OR "tricyclist"), and each set was entered into the databases. Full details of the search strategy can be found in Appendix A.

After the initial search, studies with no association to cycling were excluded, as were nonoriginal studies, and studies including children (less than 16 years old). The remaining studies were uploaded to Rayyan (Ouzzani et al., 2016), from where titles, abstracts, and full texts were independently assessed by two authors (AS & IJ) for potential relevance, based on the inclusion and exclusion criteria. Studies that AS and IJ could initially not agree on were discussed by the two authors until a consensus was reached. A third author (TWJJ) made the final decision when the two authors could not reach a consensus.

Studies were categorized based on a conceptual power balance model for para-cycling performance, which served as a framework to group the studies (Figure 1). Studies with the goal to observe, predict, increase, or manipulate the internal power (P_i), being the sum of anaerobic and aerobic metabolic power (Van Ingen Schenau & Cavanagh, 1990), were grouped under the Athlete factor. Studies with the goal to observe power output (P_o) or aimed at optimizing P_o, being the mechanical power of the athlete transferred onto the bicycle, were grouped under the Interface factor. The same is true for studies on the gross mechanical efficiency (e_g), which is the ratio between P_o and P_i. Studies on power loss in the power balance model and on observing or manipulating internal, rolling, or air resistance, or the equipment used, were grouped under the Equipment factor. For each included paper, aims, number and sex of the participants, participant performance level and impairment, division, study design, and a summary of the most important findings were described.

$$P_i \quad X \quad e_g = P_o \quad X \quad e_{bike} - P_d = dE/dt= d(1/2mv^2)/dt$$

Athlete	**Interface**	**Equipment**	**External conditions**	**Performance**
Age and sex Expertise Physical factors: Aerobic power Anaerobic power Anthropometry Distribution of power output Muscle fiber distribution Nutrition Psychological factors	Gross mechanical efficiency Bike configuration Pedaling technique Position on/in the bike Propulsion mechanism	Bike design and configuration Bike type Clothing Drive chain efficiency Helmet Internal resistance Rolling resistance Air resistance Mass Prosthetic/ orthotic	Course characteristics (distance, terrain, elevation, etc.) Gravitational resistance Influence of opponents Race conditions (temperature, air pressure, relative humidity, wind velocity and angle)	Velocity Result of factors related to Athlete, Interface, Equipment and External conditions

Impairment
Para-cycling division, sports class, and impairments

Figure 1. Conceptual power balance model of para-cycling performance.
Abbreviations: P_i: internal power, e_g: gross mechanical efficiency, P_o: power output, e_{bike}: drive chain efficiency, P_d power dissipation, dE/dt=d(1/2mv2)/dt: the change in kinetic energy of the cyclist.

Determination of participant performance level in each study was based on criteria of classification for cyclists (Jeukendrup et al., 2000), guidelines for classifying participant groups in sport-science research (De Pauw et al., 2013; Decroix et al., 2016) and indirect descriptive data in the articles regarding the level of competition, past achievements, etc. Physiological indicators, such as maximal oxygen uptake and peak power output, were not used to classify participants, as these are generally affected by impairments (Perret & Abel, 2016), and clear reference values for all para sport classes are currently lacking. Participants who were not untrained, but with otherwise unknown training level, were categorized as "trained", while para-cyclists who had trained for more than two years, at least three times and a minimum of five hours per week, in a frequent manner, were grouped as "well-trained". Para-cyclists who trained at least four times and a minimum of eight hours per week were classified as "elite". Finally, para-cyclists that competed at the highest competitive level were classified as "World-class".

Results

The flow of records identified, screened, deemed eligible, included, and excluded is in Figure 2. Of the 3373 records initially identified, 69 articles were included for this review, and eight articles were added after screening of the reference lists of the selected articles (total n = 77). The largest body of research focused on the *Athlete* (n = 28 papers) followed by *Interface* (n = 20), *Equipment* (n = 17), *Impairment* (n = 15), and *External conditions (n = 1)*. Six papers covered more than one aspect of the power balance model. No studies were found that could be grouped under *Performance velocity*. Most relevant articles included handcyclists (n = 43 papers), followed by cyclists (n = 23), tandem cyclists (n = 11) and tricyclists (n = 4).

From the further analyses, 29 (38%) of these studies included female and male participants, 26 studies (33%) included male only participants, and 11 studies (14%) were male case studies, whereas two were female case studies (3%). In eight studies (10%) the sex of the participants was not defined, and in 10 studies (13%) no participants were involved, as they were modelling and simulation studies. In total 520 (22%) females and 1760 (73%) males participated in the selected studies, and for 5% (n = 119) of the participants, their gender was not reported. When race observations were excluded, the number of participants that volunteered for these studies were 153 (19%) females and 671 (81%) males.

There were several types of studies included. The randomized controlled, case-control, or crossover design studies with cyclists with an impairment mostly involved well-trained para-cyclists or a mix of trained, well-trained, and elite para-cyclists. (i.e.. Alkemade et al. (2023); Arnet et al. (2014); Childers and Gregor (2011); Englert et al. (2018); Fischer et al. (2014); Flueck et al. (2019); Goosey-Tolfrey et al. (2008); Leicht et al. (2010); Malwina et al. (2015); Mason et al. (2021); Nevin et al. (2018); Runciman et al. (2015); Stone et al. (2019c); Wright (2015)). The cross-sectional or case studies were mostly of descriptive nature. Researchers observed the athlete during races or training and described their physiological traits (Abel et al., 2006; Antunes et al., 2022; Boer & Terblanche, 2014; Menaspa et al., 2012; Sanders et al., 2022), biomechanical traits (Barrat, 2011; Belloli et al., 2014; Brickley & Gregson, 2011; Burkett & Mellifont, 2008; Stone et al., 2019c), training load (Zeller et al., 2017), or performance differences (Borg et al., 2022; Dyer, 2018; Liljedahl et al., 2023; Liljedahl et al., 2021; Lima et al., 2021; Muchaxo et al., 2020; West et al., 2015).

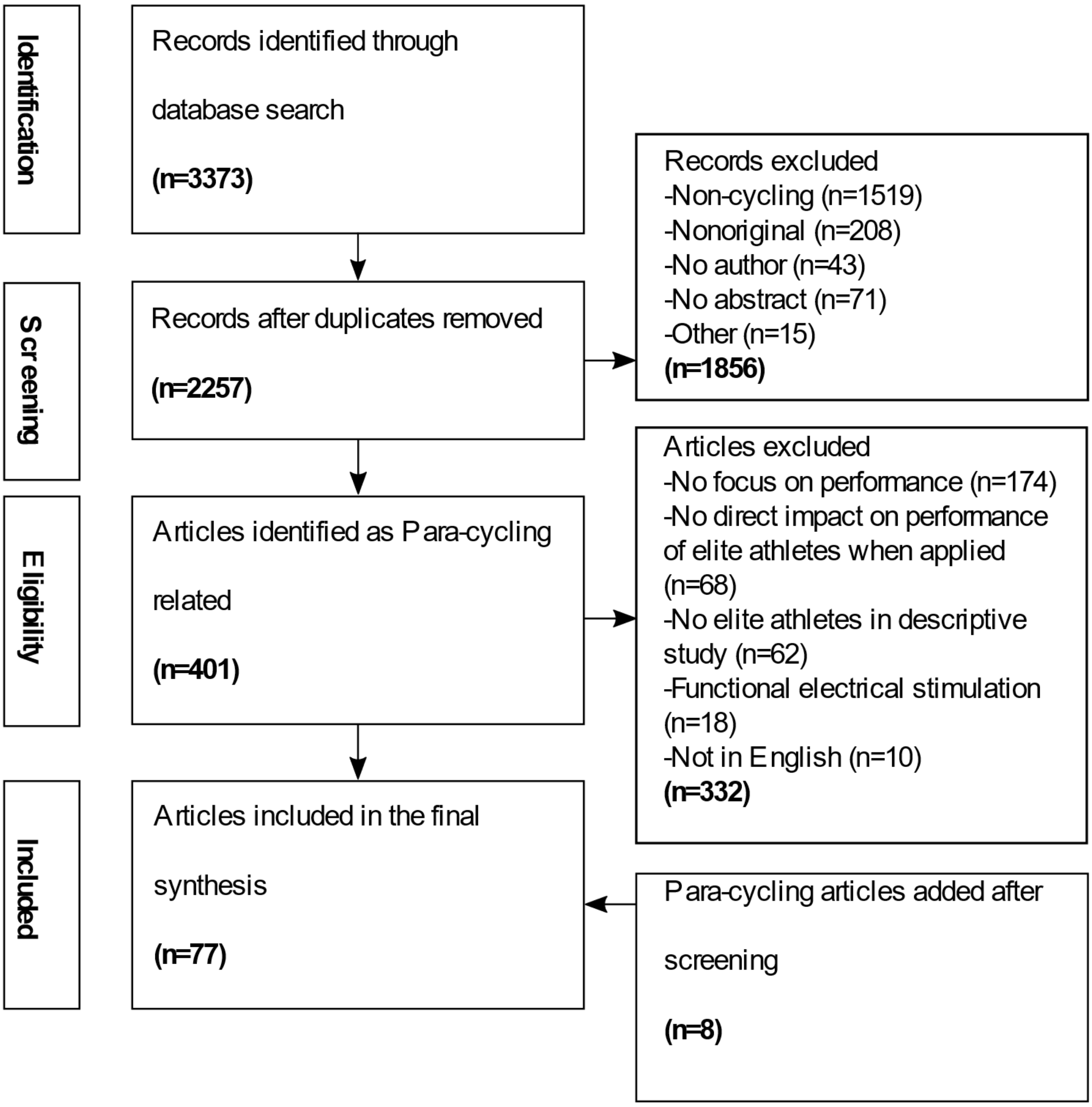

Figure 2. Flow diagram of articles identified, included, and excluded.

Some of the studies with elite to World-class para-cyclists had a limited number of participants, yet a few studies contained larger groups of high-level athletes (n=23-168) (Liljedahl et al., 2023; Muchaxo et al., 2021; Muchaxo et al., 2022; Muchaxo et al., 2023; Nooijen et al., 2021; West et al., 2015). These studies were all performed in collaboration with the Union Cycliste Internationale (UCI), where measurements were done preceding UCI World Cups and UCI World Championships. Unlike the descriptive studies, which have increased in number over the past 18 years, there are few experimental studies with elite to World-class para-cyclists (Alkemade et al., 2023; Englert et al., 2018; Goosey-Tolfrey et al., 2008). The most relevant findings in literature related to the different parameters of the power balance model are described below.

Studies related to performance factor "Athlete"

Descriptive findings on *Athlete* orientated studies can be found in Table 1. Observational studies related to the *Athlete* can be divided in two groups, namely case-studies (Abel et al., 2006; Barrat, 2011; Graham-Paulson et al., 2018; Menaspa et al., 2012; Sanders et al., 2022; Zeller et al., 2017) and cross-sectional studies (Antunes et al., 2022; Boer & Terblanche, 2014; De Groot et al., 2023; Flueck, 2020; Lepers et al., 2013; Nevin & Smith, 2021b; Nooijen et al., 2021). Case studies varied from a biomechanical analysis in sprint cycling with a below-knee prosthetic limb (Barrat, 2011) to an analysis of the training load of a female Paralympic handcyclist (Zeller et al., 2017). Cross-sectional studies varied from interpreting body composition (Flueck, 2020) to the correlation of sprint power and time trial performance (Nooijen et al., 2021).

Interventional studies with highly trained, elite, and World-class para-cyclists, with the goal to increase P_i (e.g., by means of training or nutrition), were limited and inconclusive, as some studies had a very heterogeneous population (Englert et al., 2018; Kennedy et al., 2018), did not include performance measurements (Kennedy et al., 2018), did not include information on the sex of the participants (Nevin et al., 2018), or had no control group (Kim et al., 2017). This made it hard to deduct conclusions relevant towards a specific sports class. In some studies, either the training intervention might have been too strenuous, as was the case in Leicht et al. (2010), where respiratory warm-up impaired the performance in those with paraplegia, or the dosages were inappropriate, such as in Flueck et al. (2019), where the acute dosage of beetroot or nitrate was too low to improve performance in handcycling. Finally, an already high fitness level of the participants might have resulted in a ceiling effect, as was the case in Fischer et al. (2014), where respiratory muscle training did not result in an improved performance in handcyclists.

In tandem cycling, a difference was found in performance at the 1 km time trial between cyclists with the most limited eyesight (classified as B1 and B2) and those who have little remaining eyesight (B3) (Lima et al., 2021). The authors suggested that this could be attributed to an impaired proprioception and reduced use of the ankle during pedalling in the B1 cyclists. These differences in performance most likely are not caused by differences in impairment related opportunities for training. Malwina et al. (2015) compared the training progress of cyclists with visual disability who could not train independently outdoors with matched cyclists with visual disability who could train independently outdoors. They found no differences in training progress after seven months of training between the two groups, which suggests that the ability to train independently does not explain the difference in performance between B1/B2 and B3 tandem cyclists. It should be noted that impairment classification was not reported by Malwina et al. (2015).

The two studies on the effect on performance of training 60 min per day in hypobaric hypoxia for two weeks (Kim et al., 2017; Park et al., 2020) had no control group and a small number of participants. On the other hand, the randomized controlled trial training study by Nevin et al. (2018) found some benefits for concurrent endurance and strength training over endurance training alone in handcycling, although the included training groups were also small and heterogeneous. This exemplifies the difficulties in training studies and the gap in knowledge on how to train specific groups. Case studies such as those of Abel et al. (2006); Menaspa et al. (2012); Zeller et al. (2017) could provide more insight into the training habits and physiology of successful athletes, but cannot indicate if a different approach would have yielded other results.

Table 1. Athlete related studies.

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
Abel et al. (2006)	Describing physiological data of a handcycle marathon.	1	0	1	4	SCI	H	Case study	Power output	Actual race data.
Antunes et al. (2022)	Analyzing physiological and perceptual responses during an interval workout at critical speed.	8	2	6	4	Paraplegia, tetraplegia	H	Cross-sectional study	VO2peak	Endurance interval training around critical speed could be a beneficial training intensity for handcyclists.
Barrat (2011)	The effect of a below-knee prosthetic limb on sprint cycling performance.	1	0	1	5	TTA	C	Case study	Crank torque and power	Similar crank power between the normal and the prosthetic limb, but the relative contribution of hip transfer power was larger in the prosthetic limb.
Boer and Terblanche (2014)	Ventilatory threshold to intensity, and predicting 20 km TT performance.	9	1	8	4	Amputations, CP, VI	B, C, T	Cross-sectional study	20 km TT; average and peak power	Similar heart rate at ventilatory threshold and during a 20 km TT, peak power output correlates best with TT.
Englert et al. (2018)	Ego depletion in elite athletes performing a familiar task.	13	6	7	4	CP, VI, underdeveloped limb	B, C	Randomized-crossover design	6-km TT	Ego depletion had the largest effect on the power output at the beginning of the TT.
Fischer et al. (2014)	Investigating the impact of respiratory muscle endurance training on lung function and exercise performance in athletes with high lesion level paraplegia.	12	2	10	3	Acute traumatic and complete lesion at the level of the thoracic vertebrae (ASIA A and ASIA B)	H	Case-control study	Simulated TT	Four weeks of respiratory muscle endurance training did not alter resting lung function or exercise performance.

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
Flueck et al. (2019)	Investigating the influence of a single dose of either beetroot juice or sodium nitrate on performance in a 10 km TT in individuals without disabilities and para-cyclists.	22	0	22	3/2	SCI	H	Randomized, placebo-controlled, single-blind, cross-over study	Simulated 10 km TT	No effect of nitrate supplementation on 10 km TT performance.
Flueck (2020)	To retrospectively interpret body composition in various wheelchair athletes.	69			4	Paraplegic, tetraplegic and non-spinal cord injury	H	Cross-sectional study	N/A	Lowest fat mass was found in para-cycling athletes. In tetraplegic athletes, difference in fat-free mass between left and right arms correlated with the upper extremity motor score.
De Groot et al. (2023)	Investigating the external and internal workload of trained handcyclists and compare their results with a World-class handcyclist.	11	0	11	2/5	SCI, CP, transfemoral amputation, paralyzed lower leg	H	Cross-sectional study	POmean, Mountain TT	Laboratory outcomes POpeak and PO at VT2 are important performance determinants for longer time trials in handcyclists.
Graham-Paulson et al. (2016)	Studying the effects of caffeine on cycling/ handcycling 10 km TT performance in habitual caffeine users.	11	0	11	2	Without disabilities	H	Double-blind, placebo-controlled, repeated measures	10 km TT	Caffeine significantly improved 10 km TT performance in cycling but not in handcycling.
Graham-Paulson et al. (2018)	Dose response of caffeine on 20 km TT performance in a Para-triathlete.	1	0	1	3	Paraplegia (T7, ASIA A)	H	Case study	20 km TT	Caffeine improved 20 km TT performance of an elite male Para-triathlete.
Kennedy et al. (2018)	Effect of massage therapy.	9	2	7	4	SCI, amputation, stroke, traumatic brain injury,	C, H, T	Quasi-experimental, convergent,	N/A	Significant improvement in sleep and muscle tightness.

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
						impairment in lower limb, CP		parallel, mixed-methods design		
Kim et al. (2017)	2-week intermittent hypoxic training on performance.	3			3	Incomplete cervical SCI, incomplete lumbar SCI, brain lesion	n/a	Time series	14-km TT	5.1%, 16.0% and 4.4% faster TT after the training period.
Leicht et al. (2010)	Investigating the effect of respiratory warm-up on handcycle performance.	9	0	9	3	Paraplegia	H	Randomized-crossover design	Time-to-exhaustion	Respiratory warm-up impaired performance.
Lepers et al. (2013)	Examining performance trends in NY City marathon for wheelchair (WC) and handcycle (HC) athletes in the period from 1999 to 2010.	776	141	635	N/A	N/A	H	Cross-sectional study	Time	Average race time difference between female and male winners from 1999 to 2010 was 32% SD = 16%.
Liljedahl et al. (2023)	To study the relationship between lower limb Manual Muscle Tests and cycling performance.	56	12	44	4	Impaired muscle strength and/or range of movement, transtibial amputation, transfemoral amputation	C	Cross-sectional study	Race speed	Manual Muscle Tests were associated with isometric push strength and dynamic push and pull strength, and these were associated with para–cycling performance.
Lovell et al. (2012)	1) Examining the cardiorespiratory responses of trained SCI handcyclists during maximal arm cranking. 2) Determining best predictors of 20 km race performance.	20	0	20	4/1	SCI	H	Case-control study	e_g, POpeak	The trained men had significantly higher e_g at 50 W (14.15% SD = 2.0%) and 80 W (17.2% SD = 2.6%) compared to the untrained men (50 W: 12.5% SD = 1.8% and 80 W: 15.7% SD = 2.1%).

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
Malwina et al. (2015)	Investigating the effects of 7-month training on aerobic and anaerobic capacity in tandem cycling athletes with and without visual impairment.	26			3	Visual impairment which precluded independent cycling	B	Case-control study	Sprint power	Visual impaired and properly sighted tandem cyclists showed similar rates of improvement in maximal oxygen uptake and sprint power output after 7-month training.
Menaspa et al. (2012)	Describing the physical fitness of a top-level lower limb amputee cyclist and para-cycling time trial race demands.	1	0	1	5	Unilateral transfemoral amputee	C	Case study	Mean power	Physical fitness of a transfemoral amputee trained cyclist can exceed that of age-matched people without disabilities.
Muchaxo et al. (2022)	Determining the association between isometric upper-limb strength and performance outcome.	59	13	46	4	Tetraplegia, Paraplegia, Amputee, Neurological	H	Cross-sectional study	POmean, POpeak, TT	Isometric strength outcomes are adequate sport-specific indicators of impairment in handcycling classification.
Muchaxo et al. (2023)	Determining the impact of closed-chain and open-chain conditions on the peak upper limb force produced by elite handcyclists.	62	13	49	4	Tetraplegia, Paraplegia, Amputee, Neurological	H	Cross-sectional study	N/A	Pull strength is higher in handcyclists when they can actively form a closed chain using their legs.
Nevin et al. (2018)	Investigating the effects of an 8-week concurrent strength and endurance training program in comparison with endurance training only on handcycling performance.	8			3	Bilateral above knee amputation, triple amputation, TTA, paraplegia, chronic degenerative condition of the lower limbs	H	Randomized controlled trial	30 km TT	Both concurrent and endurance training only can result in meaningfully, greater improvements in several key determinants of hand cycling performance.

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
Nevin and Smith (2021b)	Determining relation between upper-body strength and handcycling performance.	13	0	13	2	Bilateral in the knee amputation, triple amputation, paraplegia (T1-T10)	H	Cross-sectional study	TT	Large correlation between relative upper-body strength and TT velocity.
Nooijen et al. (2021)	Sprint power and time trial performance.	168	44	124	4	N/A	C, H, T	Cross-sectional study	TT	Sprint power is related to TT performance.
Park et al. (2020)	2-week training program in hypobaric hypoxia on performance.	6	2	4	2	Blind, cognitively impaired, SCI	B, H	Time series	3 km TT	3 km TT performance increased with an average of 4.4%.
Sanders et al. (2022)	Describing the 12-month preparation of a multiple medal-winning Paralympic cyclist.	1	0	1	5	Limited right arm function	C	Case Study	Critical power test, TT	Demonstration of how a multidisciplinary team of specialist practitioners successfully prepared an elite Paralympic cyclist
Wright (2015)	Investigating the pacing strategy adopted during the 1-km TT and 500-m TT in elite C1 to C3 male and female para-cyclists.	68	21	47	5	N/A	C	Case-control study	Split-time 500 m and 1 km TT	Pacing strategies for para-cyclists in both the women's 500 m TT and the men's 1 km TT showed similar patterns to elite competitors without disabilities. Split times demonstrated a positive pacing strategy.
Zeller et al. (2017)	Analyzing the training intensity distribution and the total training load of a multiple female Paralympic medalist.	1	1	0	5	Lesion level: L2-3 incomplete, ASIA C	H	Case study	POpeak	433:53 hours in 45 weeks. 71.6% SD = 14.9% in Zone 1; 15.2% SD = 8.0% in Zone 2; 13.1 SD = 5.5% in Zone 3. POpeak increased with 11%.

Abbreviations: N = number of total participants; f = number of female participants; m = number of male participants; PL = performance level (1-5: 1=untrained; 2=trained; 3=well-trained; 4=elite; 5=World-class); SCI = spinal cord injury; TTA = unilateral trans tibial amputation; ASIA = American Spinal Injury Association; CP = cerebral palsy;; VI = visual impairment; Div = Division (B = Tandem; C = Cycling; H = Handcycling; T = Tricycling); VO2peak = peak oxygen uptake; TT = time trial; POmean = mean power output; e_g = gross mechanical efficiency; POpeak = peak power output; VT2 = secondary ventilatory threshold

Studies related to performance factor "Interface"

Descriptive findings on *Interface* orientated studies can be found in Table 2. There are a number of studies on the effect of adaptations to the handcycle to improve power output, that have relatively large participant groups and a clear research design, but most of these studies are with untrained or trained participants without disabilities (Abel et al., 2015; Kouwijzer et al., 2018; Kramer et al., 2009a; Kramer et al., 2009b; Vegter et al., 2019; Zeller et al., 2015). However, four similar studies were also done with trained to elite level handcyclists (Arnet et al., 2014; Goosey-Tolfrey et al., 2008; Mason et al., 2021; Stone et al., 2019b). The most recent study concerning *Interface* (Mason et al., 2021) highlights the differences found between untrained handcyclists without disabilities, who produced greater torque during the pull phase (Vegter et al., 2019), and trained handcyclists who produced greater torque in the push phase (Mason et al., 2021), indicating a difference in technique between untrained and trained handcyclists. Also, some studies were performed with ergometer handcycles (Kramer et al., 2009a) and touring handcycles (Goosey-Tolfrey et al., 2008), which differ distinctly from the handcycles used by elite handcyclists, as these bikes require a seated posture, while elite handcyclists perform in a much more recumbent position.

The handcycling research performed by Abel et al. (2010); Groen et al. (2010); Mason et al. (2021); Stone et al. (2019b, 2019c), with trained handcyclists using race handcycles is most useful and applicable for coaches and athletes interested in Paralympic cycling performance. From these studies, it can be concluded that no statistical significant relation was found between upper limb kinematics and performance (Abel et al., 2010; Mason et al., 2021). In addition, optimal crank length could not be determined, as crank lengths between 150 and 180 mm had no differentiating effect on performance, although kinematics were significantly different for different crank lengths (Mason et al., 2021). Differences in kinematics and power output were also found between elite and well-trained handcyclists, even when handcycle configurations were similar (Stone et al., 2019c). Changing handcycle configuration could improve performance, as a horizontal crank fore-aft position was found to be the most economical (oxygen uptake at 70% peak power output) at 97-100% of arm length in well-trained handcyclists (Stone et al., 2019b), while another study found an optimal crank position of 94% (Vegter et al., 2019). It should be noted that the latter study involved untrained participants without disabilities.

Table 2. Interface related studies.

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
Abel et al. (2010)	Providing specific information on upper body kinematics in elite athletes.	13			4	N/A	H	Cross-sectional study	Paralympic TT	No significant relationship between the examined parameters describing shoulder and elbow joint kinematics and performance parameters.
Abel et al. (2015)	Examining effect of three different grip positions on physical parameters during handcycling in a laboratory setting.	21	6	15	2	Without disabilities	H	Randomized-crossover design	Power output	No differences between three different grip positions (horizontal, vertical, and diagonal) when handcycling at maximum intensity.
Arnet et al. (2014)	Identifying optimal handcycle setups.	13	4	9	2-4	SCI	H	Randomized-crossover design	e_g	A higher backrest resulted in less shoulder load with increasing e_g. The best crank position could not be identified.
Barrat (2011)	The effect of a below-knee prosthetic limb on sprint cycling performance.	1	0	1		TTA	C	Case study	Crank torque and power	Similar crank power between the normal and the prosthetic limb, but the relative contribution of hip transfer power was larger in the prosthetic limb.
Burkett and Mellifont (2008)	Individual bicycle adjustments protocol.	6	1	5	4	CP, VI, Amputation	B, C	Cross-sectional study	Power output	A system to improve bike setup can improve performance.
Goosey-Tolfrey et al. (2008)	Determining the effect of crank length and cadence on e_g.	8	0	8	4	Diverse	H	Randomized-crossover design	e_g	Crank length has effect on e_g in handcycling.
Groen et al. (2010)	Demonstrating the applicability of the power balance model to elite	4	2	2	4-5	Incomplete SCI, above knee double	H	Cross-sectional study	e_g	Power output in handcycling can described as $0.20v^3+2.90v$ (W), where v is velocity.

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
	handcycling and to obtain values for gross efficiency.					amputation, post traumatic dystrophy				
Kopacz et al. (2014)	Performing movement analysis of tandem track cyclists using a video-based system.	4			3	N/A	B	Cross-sectional study	N/A	Significant hip joint difference on the track when compared to static observation on a trainer, while all other measured joints were comparable.
Kopacz et al. (2016)	Evaluating the level of muscle tension in tandem track cyclists on a trainer and the track.	4	2	2	N/A	Aphakia, nystagmus, myopia, and VI	B	Cross-sectional study	N/A	Muscle tension was found to be higher on the track than on the trainer.
Koutny et al. (2013)	Investigating the effects of length adjustment of the crank on the kinematics and muscle activity.	1	0	1	3	TTA	C	Case study	Crank force	Crank length adjustments influence the geometric deviations between the movement of prosthetic and healthy limbs during cycling.
Kouwijzer et al. (2018)	Assessing the effects on performance and physiological responses of making a closed chain in handcycling.	10	3	7	1	Without disabilities	H	Multiple crossover design	POpeak at isokinetic sprint	The ability to make a closed chain improved handcycling sprint performance.
Kramer et al. (2009b)	To determine effect of different hand angles on force and work distribution.	25	7	18	1	Without disabilities	H	Multiple crossover design	Power output	Hand angle had most effect on pull-down and lift-up sections of the crank.
Kramer et al. (2009a)	Determining the effects of crank length and width on maximal performance.	21	5	16	1	Without disabilities	H	Multiple crossover design	Power output	Crank width did not influence maximal power. Optimal crank length is 26% of forward reach ratio.
Litzenberger et al. (2016)	Identifying the effects of a change of backrest position, crank height, and crank length on kinematics and	1	0	1	4	Paraplegic	H	Case study	N/A	There is no clear indication that a change in any of the investigated parameters of the

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
	muscular activity of an elite handcyclist.									setup would directly lead to an improvement for the athlete.
Mason et al. (2021)	Determining effect of crank length on physiological and biomechanical aspects at fixed handgrip speeds.	9	1	8	3	Complete SCI (T4–T11), incomplete spinal lesion (T8), lower limb amputees, CP	H	Multiple crossover design	Torque	Crank length has effect on peak torque, angle at peak torque, and range of movement, but not on physiological parameters.
Mazzola et al. (2012)	Determining the effects of seat and handgrips adjustments on handcycling performance.	1			N/A	N/A	H	Case study	Drag area	The best compromise can be achieved with the seatback adjusted in the intermediate inclination and the shorter hand grip levers.
Stone et al. (2019a)	Exploring how handcycling experts (elite handcyclists, coaches, support staff, and manufacturers) perceived aspects of recumbent handcycle configuration to impact upon endurance performance.	14	3	11	Ex-perts	Mixed	H	Qualitative study	N/A	Optimizing the handcycle for comfort and stability, primarily via backrest padding and power production, the position of the shoulders relative to handgrips and crank axis, were critical.
Stone et al. (2019b)	Determining the effects of horizontal crank position on economy and upper limb kinematics in recumbent handcycling.	15	2	13	3	Complete SCI (T6–T11), incomplete SCI (T5–L1), lower limb amputees, CP, fibromyalgia	H	Cross-over study	N/A	Positioning the cranks at 97% to 100% of the athletes' arm length improved handcycling economy at 70% POpeak.
Stone et al. (2019c)	Evaluating and comparing the upper limb kinematics and handcycle configurations of recreational and competitive recumbent	13	0	13	4/3	N/A	H	Cross-sectional study	Sprint power	Larger extension of shoulders (~5°) and flexion of thorax (~10°) at training and competition intensities while an increase in scapular posterior tilt (~15°, $P < 0.05$)

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
	handcyclists, during sport-specific intensities.									only occurred at competition intensity. No kinematic differences during sprinting.
Vegter et al. (2019)	Investigating the effect of four different crank fore-aft positions.	12	0	12	1	Without disabilities	H	Cross-over study	e_g	The crank position closest to the trunk (94%) seems to be advantageous.
Zeller et al. (2015)	Examining the influence of a noncircular chainring compared with a conventional circular chainring on handcycling performance.	11	0	11	1	Without disabilities	H	Cross-over study	POpeak, peak and average power output during sprint	No performance improvement with non-circular chainring.

Abbreviations: N = number of total participants; f = number of female participants; m = number of male participants; PL = performance level (1-5: 1=untrained; 2=trained; 3=well-trained; 4=elite; 5=World-class); SCI = spinal cord injury; TTA = unilateral trans tibial amputation; CP = cerebral palsy;; VI = visual impairment; Div = Division (B = Tandem; C = Cycling; H = Handcycling); TT = time trial; e_g = gross mechanical efficiency; POpeak = peak power output

Studies related to performance factor "Equipment"

Descriptive findings on Equipment orientated studies can be found in Table 3. One group of authors did extensive research on aerodynamics in handcycling and tandem cycling (Mannion et al., 2018a, 2018b; Mannion et al., 2019a, 2019b; Mannion et al., 2019c; Mannion et al., 2019d; Mannion et al., 2019e). Using computational fluid dynamics and wind tunnel tests, many different effects on aerodynamics were determined that could directly be implemented by athletes and coaches. In handcycling for instance, Mazzola et al. (2012) had suggested using front and rear disc wheels to reduce aerodynamic drag, but Mannion et al. (2018b) further elaborated on this and indicated that disc wheels increase lateral forces and create a low-pressure region between the rear wheels (Mannion et al., 2019a). Therefore, a front disc wheel and high-rim spoked wheels constitute the best wheel configuration for handcyclists (Mannion et al., 2019e). In tandem cycling, according to the studies, the most aerodynamic tandem setup is one where the pilot is in time trial position, with a maximum torso angle of 25o, and the stoker clenching the frame below the saddle of the pilot, with a torso angle lower than that of the pilot (Mannion et al., 2018a; Mannion et al., 2019b). An aerodynamics study performed by Dyer et al. (2022b) in a wind tunnel with real tandem cyclists confirmed these limitations, as the coefficient of variation during the test with one tandem couple was higher than 2%, which was considered unacceptable, as it exceeded the maximum coefficient of variation of 2% as recorded by cyclists without disabilities (García-López et al., 2008).

Other findings for elite athletes and coaches regarding Equipment come from studies on prosthetic design in those with a lower-leg prosthesis. From the studies, an aerodynamically shaped lower-leg prosthesis (airfoil design) can reduce time trial time by 0.4-1.8% (Childers et al., 2015; Dyer & Disley, 2020), and up to 4.9% when pedalling asymmetry is minimized (Childers et al., 2015), while these prostheses can be made with lower mass than the standard round prosthesis (Dyer & Woolley, 2017).

Table 3. Equipment related studies.

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
Baur et al. (2008)	Biomechanical performance characteristics of an athlete with paresis of the peroneal muscle, and the effect of an orthosis	1	1	0	4	SCI	C	Case study	Power output	Orthoses increase ankle stability
Belloli et al. (2014)	Investigating the effect of the athlete on aero-dynamic drag.	2	0	2	5	N/A	H	Case study	Drag area	Large differences in between aerodynamic position and pedaling position. These were negligible in MH2.
Childers et al. (2015)	Understanding the effect of a TTA on Olympic 4-km pursuit performance	N/A			N/A	TTA	C	Modelling	4-km pursuit time	Cyclists with a TTA can theoretically be as fast as an Olympic cyclist without disabilities.
Dyer and Disley (2020)	Optimizing aerodynamic design of prosthetics	1	0	1	4	Unilateral lower limb amputation	C	Case study	Drag area	Prostheses that had a deep airfoil design were more aerodynamic than those with a round section.
Dyer and Woolley (2017)	Developing a prosthetic limb for competitive cycling	1	0	1	4	Unilateral lower limb amputation	C	Case study	Mass	An airfoil shaped prosthetic, with reduced mass and evaluated at the exercise intensity of the cyclist's events.
Dyer (2018)	Determining the differences between C4 cyclists with a lower-limb prosthesis and those that do not	116	0	116	4-5	Lower-limb amputation and other C4 related impairments	C	Cross-sectional study	1-km TT time	No difference between C4 cyclists with a lower-limb prosthesis and opponents in the same class that do not require a lower-limb prosthesis.
Dyer et al. (2022a)	Developing a prosthetic limb for elite para-cycling using 3D printing	1	0	1	4	Upper-limb amputation	C	Case study	N/A	Successfully developed a high-performance prototyped arm prosthesis using 3D printers.
Dyer et al. (2022b)	Determining aerodynamic drag in live tandem para-cyclists in a wind tunnel	4	2	2	4	VI	B	Case study	Drag area	Greatest improvements trough aerodynamic interventions were lowering front handlebars

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
										(7.4%) and lowering heads of both riders (5.3%).
Groen et al. (2010)	Demonstrating the applicability of the power balance model to elite handcycling and to obtain values for gross efficiency	4	2	2	4-5	Incomplete SCI, above knee double amputation, post traumatic dystrophy	H	Cross-sectional study	e_g	Power output in handcycling can be described as $0.20v^3+2.90v$ (W), where v is velocity.
Mannion et al. (2018b)	Analyzing the aerodynamics of competitive handcycling under crosswind conditions using wind-tunnel experiments and Computational Fluid Dynamics simulations	N/A			N/A	N/A	H	Aerodynamics study	Drag area	The drag in a road setup increased by 14.1% from 0 to 15 yaw, but TT setup increased 3.3%, from 0 to 5 yaw. The lateral force in the TT exceeded the drag at 20 yaw by 5.6 times, in comparison to 1.6 times for the road setup.
Mannion et al. (2019c)	Determining the impact of arm-crank position on the drag of a Paralympic handcyclist	N/A			N/A	N/A	H	Aerodynamics study	Drag area	The 3 and 12 o'clock positions (when observed from the left side) yielded the highest drag area at 0 yaw, while the 9 o'clock position yielded the lowest drag area for all yaw angles .
Mannion et al. (2019e)	Determining handcycling wheel aerodynamics.	N/A			N/A	N/A	H	Aerodynamics study	Drag area	A front disc wheel in combination with rear spoked wheel with 55 cm spacing was the most aerodynamic.
Mannion et al. (2019a)	Determining the effect of wheel size on aerodynamic drag	N/A			N/A	N/A	H	Aerodynamics study	Drag area	Drag reductions of up to 8.9% were found when utilizing 20-inch diameter spoked wheels, opposed to the 26-inch wheels.
Mannion et al. (2018a)	Analyzing aerodynamic drag acting on two tandem road	N/A			N/A	N/A	B	Aerodynamics study	Drag area	The most aerodynamic tandem setup was found to be the frame-clench setup.

Study	Aims	N	f	m	PL	Impairment	Div	Study design	Perf. M.	Summary of findings
	race setups and two tandem track time trial setups									
Mannion et al. (2019b)	Studying the aerodynamics of tandem cyclists considering 23 different torso angle combinations	N/A			N/A	N/A	B	Aerodynamics study	Drag area	Increasing the torso angle more than 25° for either athlete caused detrimental effects on the frontal drag area of the tandem setup.
Mannion et al. (2019d)	Investigating the drag and lateral forces at yaw angles between 0◦-20◦ using full-scale computational fluid dynamics	N/A			N/A	N/A	B	Aerodynamics study	Drag area	Frontal drag area was 0.311 m^2 for 0◦ yaw, which increased to 0.337 m^2 at 15◦. Reduction in drag was found at 20◦ with a frontal drag area of 0.305 m^2.
Riel et al. (2009)	Design of a specifically made prosthesis kit	1	0	1	5	Trans-humeral amputation	C	Case study	N/A	Prosthetic arm that can be used in all disciplines.
Mazzola et al. (2012)	Determining the effects of seat and handgrips adjustments on handcycling performance	1			N/A	N/A	H	Case study	Drag area	The best compromise can be achieved with the seatback adjusted in the intermediate inclination and the shorter hand grip levers.
Seo and Eda (2018)	Determining the influence of the phase difference between the crank angle of the pilot and that of the stoker on the drag on a tandem bike	N/A			N/A	N/A	B	Aerodynamics study	Drag area	Drag was found to be the lowest when the crank of the stoker was 60° behind the crank of the pilot.
Solazzi et al. (2022)	To evaluate the performance of a handcycle fork made from carbon-fiber composite material compared to traditional aluminum model	N/A			N/A	N/A	H	Case study	Drag area	The handcycle fork reduced weight with 30% and increased aerodynamic efficiency with 58%.

Abbreviations N = number of total participants; F = number of female participants; M = number of male participants; PL = performance level (1-5: 1=untrained; 2=trained; 3=well-trained; 4=elite; 5=World-class); SCI = spinal cord injury; TTA = unilateral trans tibial amputation; VI = visual impairment; Div = Division (B = Tandem; C = Cycling; H = Handcycling; T = Tricycling); Perf. M. = performance measure; e_g = gross mechanical efficiency; TT = time trial; MH = men handbike sports class

Studies related to performance factor "Impairment"

Descriptive findings on Impairment orientated studies can be found in Table 4. In three studies race velocities were compared between the different classes in road race (Borg et al., 2022; Muchaxo et al., 2020) and men's 1 km time trial on the track (Liljedahl et al., 2021). They found that in men, race velocities differed significantly ($p<0.01$) between consecutive C classes (C1-C2, C2-C3, C3-C4), but not between C4 and C5, while no differences were found between consecutive women C classes, probably due to the lower number of participants (Borg et al., 2022; Liljedahl et al., 2021). Significant differences ($p<0.01$) were also found between consecutive H classes, but not between H4 and H5 (Muchaxo et al., 2020). Lastly, men and women's T1 and T2 performances in the road race were also found to be significantly different ($p<0.001$)(Borg et al., 2022). This indicates that the performance in para-cycling is hierarchical for the athletes with the greatest impairments, with lowest performance with the most severe impairments (C1, C2, H1, H2, T1, T2), but that no performance differences were found for the athletes with the least severe impairments (C4, C5, H4, H5).

Based on their study Muchaxo et al. (2020) suggest that there is no justification based on average velocity for the current cutoffs between the least impaired classes. To be able to better relate impairment to performance and sport classes, some researchers have started to investigate the relation between different impairments and performance abilities in para-cycling (trunk function on handcycling performance (Muchaxo et al., 2021; Muchaxo et al., 2022; Muchaxo et al., 2023); muscle strength on cycling performance (Liljedahl et al., 2023); sprint power on para-cycling performance (Nooijen et al., 2021). However, the results are inconclusive, as the impact of specific impairments on performance, such as cycling with one or two legs with and without upper body impairment, is yet unknown, and more research is needed to come to an evidence-based classification system in para-cycling.

Table 4. External conditions and Impairment related studies.

Study	Aims	N	f	m	PL	Impairment	Div	Study des.	Perf. M.	Summary of findings
Alkemade et al. (2023)	Comparing the effect of hot-humid environmental conditions on performance between athletes with and without disabilities.	40	21	19	4	Lower limb deficiency, n =9 (unilateral n =5, bilateral n =4), SCI (paraplegia), n =4 VI, n =2, Other physical impairments, n =5	N/A	Mixed crossover design	POpeak, TTE	Similar heat-induced performance decrements between elite athletes with and without disabilities.
Borg et al. (2022)	Describing cycling and tricycling performance in international para-cycling road race events between 2011 and 2019.	523	112	411	4	N/A	C, T	Cross-sectional study	Mean race velocity	Statistical difference between: MC1-MC2; MC2-MC3; MC3-MC4; MT1-MT2; WT1-WT2. No statistical differences between other adjacent classes.
Brickley and Gregson (2011)	Investigating differences in torque production of an elite cyclist with CP.	1	0	1	5	CP	C	Case study	Mean peak torque in each leg	Significant differences in torque production between legs, which decreased as cadence increased
Childers et al. (2011)	1) Quantifying the amount of pedaling asymmetry in cyclists with a TTA; 2) Investigating the effect of prosthetic foot stiffness.	17	3	14	2-5	TTA	C	Non-randomized controlled trial	N/A	Cyclists with a TTA have greater pedaling asymmetry than cyclists without disabilities and depend more on their sound limb for force and work production.
Childers et al. (2015)	Understanding the effect of a TTA on Olympic 4-km pursuit performance.	N/A			N/A	TTA	C	Modelling	4-km pursuit time	Cyclists with a TTA can theoretically be as fast as an Olympic cyclist without disabilities.
Dyer (2018)	Determining the differences between C4 cyclists with a lower-limb	116	0	116	4-5	Lower-limb amputation and other	C	Cross-sectional study	1-km TT time	No difference between C4 cyclists with a lower-limb prosthesis and opponents in

Study	Aims	N	f	m	PL	Impairment	Div	Study des.	Perf. M.	Summary of findings
	prosthesis and those that do not.					C4 related impairments				the same class that do not require a lower-limb prosthesis.
Liljedahl et al. (2021)	Determining the differences in race performance between para-cycling classes.	111	0	111	5	N/A	C	Cross-sectional study	1-km TT time	Each adjacent class, except for C4 and C5, presented statistically significant differences in average time trial speed. C1-C2 and C4-C5 both have an overlap in range of performances.
Liljedahl et al. (2023)	Determining relation between dynamic and isometric leg strength and performance.	56	12	44	4	Leg impairments: impaired muscle strength and/or impaired passive range of motion	C	Cross-sectional study	TT	Degree of lower limb impairments have impact on sprint power and race performance.
Lima et al. (2021)	Determining differences in visual disability on 1-km time trial performance.	427	176	251	4	VI	B	Cross-sectional study	1-km TT	B3 athletes performed better compared to B1 and B2.
Muchaxo et al. (2020)	Determining differences in TT performance between handcycling classes.	353	70	283	4	N/A	H	Cross-sectional study	TT	Significant differences in race performance in consecutive recumbent classes.
Muchaxo et al. (2021)	Determining relation between trunk function and performance.	81	17	64	4	SCI	H	Cross-sectional study	TT, Force	Trunk function and flexion strength have minor impact on time trial performance.
Muchaxo et al. (2022)	Determining the association between isometric upper-limb strength and performance outcome.	62			4	Tetraplegia, Paraplegia, Amputee, Neurological	H	Cross-sectional study	POmean, POpeak, TT	Isometric strength outcomes are adequate sport-specific indicators of impairment in handcycling classification.
Muchaxo et al. (2023)	Determining the impact of closed-chain and open-chain conditions on the peak upper limb force	62			4	Tetraplegia, Paraplegia, Amputee, Neurological	H	Cross-sectional study	N/A	Pull strength is higher in handcyclists when they can actively form a closed chain using their legs.

Study	Aims	N	f	m	PL	Impairment	Div	Study des.	Perf. M.	Summary of findings
	produced by elite handcyclists.									
Runciman et al. (2015)	Sprint cycle performance of elite Paralympic athletes with CP during a fatiguing maximal cycling trial compared to well-trained, sprint performance-matched athletes without disabilities.	21		21	4	CP	C	Case-control study	Power output	Sprinters without disabilities produce more power than sprinters with CP, but fatigue index and muscle activation level is similar.
Watanabe et al. (2020)	Describing neuromuscular activation of lower extremity muscles in two cyclists with single leg amputation and one cyclist with two legs during pedaling.	3	1	1	4	Single-leg amputation	C	Case study	N/A	Characteristic neuromuscular coordination in the muscles contributing to hip and knee flexion joint moments during the pulling phase to compensate the lack of hip and/or knee extension torque from contralateral leg.
West et al. (2015)	Relationship between level of injury, completeness of injury, resting as well as exercise hemo-dynamics, and endurance performance in athletes with spinal cord injury.	23	0	23	3-5	SCI (cervical and thoracic)	H	Cross-sectional study	TT	Higher seated systolic blood pressure and superior TT performance with a thoracic SCI compared with a cervical SCI. Cyclists with cervical autonomic incomplete SCI were faster than cyclists with cervical autonomic complete SCI.

Abbreviations N = number of total participants; f = number of female participants; m = number of male participants; PL = performance level (1-5: 1=untrained; 2=trained; 3=well-trained; 4=elite; 5=World-class); SCI = spinal cord injury; VI = visual impairment; CP = cerebral palsy; TTA = unilateral trans tibial amputation; Div = Division (B = Tandem; C = Cycling; H = Handcycling; T = Tricycling); Study des. = study design; Perf. M. = performance measure; POpeak = peak power output; TTE = time to exhaustion; TT = time trial; POmean=mean power output; MC = men cycling sports class; MT = men tricycle sports class; WT = women tricycle sports class

Discussion

This scoping review aimed to provide an overview of relevant studies for elite para-cycling performance and to identify gaps in research. It shows the diversity of the field of para-cycling research, consisting of athletes with many different impairments and in four different para-cycling divisions, namely cycling, handcycle, tandem and tricycle. We identified several practical matters regarding the Athlete, the Interface, the Equipment, and the Impairment, that might help coaches and elite athletes to improve performance. We conclude that research on para-cycling performance faces some serious challenges, which are described below.

One of the challenges of this research field is that the number of athletes per sports class per nation is very low. Therefore, studies with athletes from one nation will include only a limited number of elite athletes per sports class and type of impairment, resulting in studies that will probably be underpowered. For example, Boer and Terblanche (2014); Burkett and Mellifont (2008); Kennedy et al. (2018) used athletes from different divisions for their study, which makes it hard to interpret the results. However, a few studies managed to include large numbers of athletes per sports class, which were studies performed during UCI World Cup events and UCI World Championships (Liljedahl et al., 2023; Muchaxo et al., 2021; Muchaxo et al., 2022; Muchaxo et al., 2023; Nooijen et al., 2021). This collaboration with the UCI makes it possible to include and analyze a large and diverse group of well-trained, elite, and even World-class athletes and produce meaningful results. The UCI should continue to stimulate international research collaborations, that can do measurements with athletes from different countries, to grow para-cycling as a sport by increasing the body of knowledge.

A second challenge of this research field is that large individual differences among athletes exist. Although this is inherent to Paralympic sports, these large individual differences make it more difficult to interpret results than when these were derived from a homogenous group of athletes. For example, even with research with athletes within the same para-cycling division it is difficult to compare individual athletes, as the participants of one study may have SCI, CP, transfemoral amputation, or paralyzed lower legs (De Groot et al., 2023), or bilateral in the knee amputation, triple amputation, and paraplegia from T1-T10 (Nevin & Smith, 2021a). That is one of the reasons why some authors choose to also conduct research including more homogenous groups without disabilities, for example to evaluate different training programs (Schoenmakers et al., 2016). However, groups without disabilities are mostly not well-trained and might therefore have a different technique or specific fitness than well-trained or elite athletes. Again, when it comes to performance enhancement research, it would be optimal to include large groups of homogenous Para-athletes which could be accomplished through international collaboration. The UCI can improve the quality and relevance of research projects by helping the researcher in the recruitment of participating cyclists (Tweedy et al., 2016).

Training studies are difficult to conduct, and in a Paralympic setting even more so, as the numbers are smaller than in sports without disabilities and the impairments are so diverse that individual adaptations might be more diverse than in a more homogenous group without disabilities. Results from training studies that were included in this review therefore need to be approached with caution.

Furthermore, it has been found that interventions from research with athletes without disabilities (e.g. respiratory muscle endurance training and nitrate ingestion) do not always sort similar effects in para-cyclists (Fischer et al., 2014; Flueck et al., 2019). Even more, a single intervention (respiratory warm-up) that was successful in sports with athletes without disabilities (Lin et al., 2007), produced negative results in para-cycling (Leicht et al., 2010).

Possible reasons for this are that the adapted protocol for athletes without disabilities was too strenuous or too light for the cyclists involved. Researchers need to beware of the fitness level of the cyclists and adapt the protocol to their level.

Female participants were underrepresented in para-cycling research (19% female), which could be attributed to the lower number of competitive female para-cyclists (27% female) when compared to male competitive para-cyclists (Borg et al., 2022; Lima et al., 2021; Muchaxo et al., 2021; Wright, 2015). However, this ratio of competitive female vs male para-cyclists is comparable to the ratio of WorldTour cyclists (26% vs 74% respectively, www.uci.ch). Nevertheless, this phenomenon is seen across sport science research (Costello et al., 2014). This raises several challenges, such as translating mainly male research findings to female applications. These translations of findings are not trivial, considering the biological differences between the two groups. This could result in differences in propulsion techniques and gross mechanical efficiency (Chaikhot et al., 2018). Therefore, more studies with female participants and with a clear distinction between female and male results should be encouraged.

Research gaps

Although the number of performance related studies in para-cycling is increasing, the research topics, study designs, performance measures, and number of participants have been diverse, and research on para-cycling has only been scratching the surface of what is possible and needed to increase performance and to develop the sport (Dyer, 2016; Kraaijenbrink et al., 2021; Nevin et al., 2022; Stephenson et al., 2021). Defining research gaps here might help coaches and researchers, but also governing bodies, to structure their own research program.

Athlete

There were several observational studies and case studies with well-trained, elite, or World-class para-cyclists. Many of these studies used time trial performance as performance indicator. However, to gain more knowledge about the athletes themselves, para-cycling needs more studies that describe physiological, biomechanical, and psychological characteristics of the athletes, so these characteristics can be used to identify benchmarks for talent identification, talent development, training, and selection (Messias et al., 2017; Zhao et al., 2019). The results in these studies should distinguish sex, division, performance level, and sports class in the results, so practitioners would be able to recognize performance indicators for each sub-group.

While minimally impaired athletes might use research and practice on athletes without disabilities for their training programs, e.g., athletes with an SCI might require a different approach on training, as their exercise capacity is inversely related to their lesion level (see Theisen (2012) for an overview on exercise capacity in Paralympic athletes with an SCI). It is possible that a training program for cyclists without disability might not work or work not as well in this group (Alves et al., 2021), and more research is needed on the training intensity distribution of the severely impaired para-cyclists. Furthermore, more studies on training cyclists with an impairment in general are needed, preferably through randomized controlled trials, although getting enough participants could be challenging. A mixed approach, where research with athletes without disabilities is done first to learn more about a specific training strategy, followed by a specific study with para-cyclists, might be the best approach to manage the small numbers of para-cyclists. However, we have not seen this strategy applied yet.

Pacing is the goal directed distribution and management of effort across the duration of an exercise bout (Edwards & Polman, 2012) and can be seen as a process of decision-making related to when and how to distribute energy over the race (Smits et al., 2014). In sports with athletes without disabilities it is well known that pacing can significantly influence performance outcomes (Abbiss & Laursen, 2008). However, in para-cycling, we could only find one study on pacing behaviour (Wright, 2015). More research on pacing and other competition factors in para-cycling such as tactics and the impact of racing against other competitors, would be of interest to further improve performance (Konings & Hettinga, 2018), especially since the complex skill of pacing has been found to be impaired when cognitive functions are impaired (Van Biesen et al., 2016).

There is a nutritional research gap in para-cycling, as we find very few studies on para-cyclists' body composition and nutritional needs, and on the effects of ergogenic supplements, such as caffeine and nitrate, on performance. The latter has been well studied in sports with athletes without disabilities (Shen et al., 2019), but the effects of the supplements on para-cycling performance remain unclear, as we found only one study on nitrates in handcycling (Flueck et al., 2019), and two studies on caffeine in handcycling, with opposite conclusions (Graham-Paulson et al., 2016, 2018). Para-cyclists can have different nutritional needs when compared to cyclists without disabilities, due to differences in body composition, metabolism, training load and habitual activity (Scaramella et al., 2018), but there is a lack of research on how to advise nutritional intake to improve performance in para-cyclists. This raises concerns, as para-athletes tend to have a high consumption of supplements (Madden et al., 2017) and medication use through therapeutic use exemptions (Alexander et al., 2022), but still fail to meet recommended daily requirements on certain micronutrients (Madden et al., 2017).

Interface

We found 21 studies that focused on optimizing the rider-bike interface, mainly on handcycling. However, the results remain inconclusive, as most studies included participants without disabilities, as these are probably easier recruitable to the researcher. Also, on some occasions the handcycles used were quite different from the handcycles used by competitive handcyclists, as these were probably the handcycles available at the lab. More research is needed on handcycling configuration with race handcycles and well-trained or better handcyclists. Furthermore, scientific knowledge on how to adapt bicycles and tricycles for specific disabilities is lacking. We think para-cycling could benefit from an overview of practical, innovative, and science-based solutions for the different bike fitting problems, compiled by researchers and practitioners in the field. Preferably through a website with photos and descriptions of various impairments and the practical solutions.

For tandem cycling, the *Interface* is not only between the cyclist and the bike, but also between the pilot and the stoker. A first attempt to describe their mechanical interaction was done by Mohammadi-Abdar et al. (2014), but more research is needed to understand the interaction between pilot and stoker and how this interaction is related to overall performance. This requires measuring pedal force of pilot and stoker during cycling.

Equipment

Based on the studies we found on air resistance, the linear transformation from cycling without disabilities to para-cycling is not valid. For example, the best compromise between aerodynamics and stability in handcycling seems to be a front disc wheel in combination with rear spoked wheels (Mannion et al., 2018b; Mannion et al., 2019e). However, this is contrary to the advice often given to cyclists in road cycling time trials, where a spoked front wheel and disc rear wheel is considered to be the best compromise between aerodynamics and stability on the bicycle (Malizia & Blocken, 2020). Also, most cycling material is designed for use on regular single bicycles, so it is unknown what the effects of, for example, helmets and clothing are on aerodynamics, when riding on a tandem or when lying down in a recumbent handcycle. Furthermore, tandem cycling research with computational fluid dynamics has used simulated copies for pilot and stoker, while varied sizes and anatomic features for pilot and stoker would be more realistic. More research on the aerodynamics of these specific bicycles such as the tandem, and tricycles, such as the handcycle and tribike, but also on the effects of specific adaptations to a regular race bicycle, are needed. When these studies are done with computational fluid dynamics, attention should be paid to inclusion of more realism regarding rotational parts, surface smoothness, and athletes on the bike.

The drive chain efficiency is one aspect of the power balance model, as it determines how much of the external generated power is transferred to the environment for propulsion. However, it may be that in tandem cycling or handcycling this is different from a normal race bicycle due to the double chain or longer chain. Yet, no information was found on the drive chain efficiency of tandems and handcycles. Future studies should focus on determining the drive chain efficiency for tandem and handcycle, to get more realistic models and determine performance improvements through minimizing power loss.

Impairment

There are several very recent studies on impairment and sports class differences, with the goal to improve the classification process. These studies were done in collaboration with the UCI. This path of evidence-based classification, which was instigated by the International Paralympic Committee (Tweedy et al., 2014; Tweedy & Vanlandewijck, 2011), should be continued to improve the classification process in para-cycling, resulting in a more valid classification procedure. This is very important for the Paralympic sport in general and for para-cycling in particular, as it will result in more attractive sport for competitors and spectators, by controlling the impact of the impairment on the outcome of the race (Tweedy & Vanlandewijck, 2011).

Different studies found that the performance in para-cycling is hierarchical for the athletes with greatest impairments, while no performance differences were found for the athletes with the least impairment (Borg et al., 2022; Muchaxo et al., 2020). This implies that the impact that the classification result has on the medal chances of an athlete that is classified in a class for athletes with a minor impairment (e.g. C5 instead of C4) is less than when an athlete is classified in a class for cyclists with the most severe impairments (e.g. H2 instead of H1).

Limitations

This study is based on the choices made to include or exclude specific studies. Although we tried to be as thorough as possible, and the selection was done by two authors, blinded to each other, some of the selection criteria were more subjective than others. For example, one of the bases for eligibility was “performance enhancements that could have a direct impact on elite para-cycling performance.” This left the decision making open to interpretation and discussions may arise on why specific studies were included or not. Also, it must be noted that lessons learned from high performance cycling studies with athletes without disabilities were beyond the scope of this review. Therefore, this scoping review did not contain a complete overview of all relevant para-cycling performance enhancement studies, only those derived from a para-cycling environment.

Perspectives

To the authors knowledge, this is the first study that reviewed available literature on para-cycling, incorporating studies on all divisions and sport classes. It highlighted research that has focused on para-cycling performance, but also revealed the many gaps in research that exist. This study found several practical matters regarding training, bike fitting, aerodynamics, and prosthetics design to help coaches and elite athletes to improve performance. However, the current state of the research is that results are scattered over many different areas and more research is needed in all sports classes to be able to provide evidence-based support for athlete and coach decision-making, and thereby enhance performance and develop the sport.

Despite increased scientific attention towards specific divisions in para-cycling, mainly handcycling (Kraaijenbrink et al. (2021); Nevin et al. (2022); Stephenson et al. (2021)), major research gaps were found. Therefore, eight gaps were identified that need to be prioritized. These gaps are a lack of 1) observational studies of physiological, biomechanical, and psychological characteristics of well-trained, elite and World-class cyclists, 2) interventional training studies with sufficient statistical power on athletes with a more severe impairment, 3) research on body composition and nutritional needs, 4) research on pacing, 5) research on optimizing bike configuration in para-cycling, 6) research on optimizing para-cycling specific equipment and reducing air resistance, 7) research on drive chain efficiency in handcycling and tandems, and 8) research on impairments to improve the classification process. Collaboration between researchers, coaches, and governing bodies is required to fill these gaps in knowledge.

Author affiliations:
[1] Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, Van der Boechorststraat 7-9, 1081 BT, Amsterdam, the Netherlands; j.j.de.koning@vu.nl; m.hofmijster@vu.nl; t.w.j.janssen@vu.nl
2 Koninklijke Nederlandsche Wielren Unie, Papendallaan 49, 6816 VD, Arnhem, the Netherlands; albert.smit@knwu.nl
3 Sport Science and Innovation, Sport Centrum Papendal, Papendallaan 9, 6816 VD, Arnhem, The Netherlands; ina.janssen@papendal.nl
4 Department of Sport, Exercise and Rehabilitation, Faculty of Health and Life Sciences, Northumbria University, Newcastle upon Tyne, NE1 8ST, United Kingdom; florentina.hettinga@northumbria.ac.uk
5 Amsterdam Rehabilitation Research Center | Reade, Overtoom 283, 1054 HW, Amsterdam, the Netherlands
6 Center for Adapted Sports Amsterdam, Amsterdam Institute of Sport Science, Amsterdam, the Netherlands
* Correspondence: albert.smit@knwu.nl; Tel.: +31 6 13 30 47 40

Author Contributions: Conceptualization, AS, FH; Methodology, AS; Formal Analysis, AS, IJ; Writing-Original Draft Preparation, AS, IJ, JdK, TJ; Writing-Review & Editing, AS, IJ, JdK, TJ, FH, MH.

Funding: This research received no external funding.

Conflicts of Interest: At the time of submission, FH was not the editor-in-Chief of EUJAPA. The manuscript was handled completely by the EUJAPA Assistant Editor. FH did not influence the decision to publish the manuscript. All other authors declare no conflict of interest.

Appendix A – Search terms and results.

Database	Keywords	Found	Duplicates
SportDiscus	Para-cycling OR paracycling OR (paralympic AND cycling) OR para-cyclists OR (paralympic AND cyclist) NOT spectrometry NOT cell NOT genome Excluding magazines	97	
	handbike OR handcycle OR handcyclist* OR handcycling OR handbiking OR (“hand cycling”) OR (“hand cycle”) (limits: academic journals and books)	174	
	(tandem AND cycling) OR (tandem AND bike) OR (tandem AND bicycle) OR (tandem AND cyclist)	39	
	(Amputation AND cycling) OR (amputation AND cyclist) OR (amputee AND cycling) OR (amputee AND cyclist) OR (prostheses AND cycling) OR (prostheses AND cyclist) OR (prosthesis AND cycling) OR (prosthesis AND cyclist) OR (prosthetic AND cycling)	63	

	OR (prosthetic AND cyclist) NOT spectrometry NOT cell NOT genome ; (limits: academic journals and books)		
	(Cerebral AND Palsy AND cycling) OR (Cerebral AND Palsy AND cyclist*) NOT (children or kids or youth or child)	27	
	Tricycling OR tricycle OR tribike OR tricyclist* NOT (children or kids or youth or child)	37	
	Total	437	
Pubmed	Para-cycling[tiab] OR paracycling[tiab] OR (paralympic AND cycling[tiab]) OR para-cyclist*[tiab] OR (paralympic AND cyclist[tiab])	78	
	Handbike*[tiab] OR handcycle*[tiab] OR handcyclist*[tiab] OR handcycling[tiab] OR handbiking[tiab] OR ("hand cycling") OR ("hand cycle")	192	
	(tandem*[tiab] AND cycling[tiab]) OR (tandem*[tiab] AND bike*[tiab]) OR (tandem*[tiab] AND bicycle*[tiab]) OR (tandem*[tiab] AND cyclist*[tiab]) AND sport	27	
	(Amputation[tiab] AND cycling[tiab]) OR (amputation[tiab] AND cyclist[tiab]) OR (amputee[tiab] AND cycling[tiab]) OR (amputee[tiab] AND cyclist*[tiab]) OR (prostheses[tiab] AND cycling[tiab]) OR (prostheses[tiab] AND cyclist*[tiab]) OR (prosthesis[tiab] AND cycling[tiab]) OR (prosthesis[tiab] AND cyclist*[tiab]) OR (prosthetic*[tiab] AND cycling[tiab]) OR (prosthetic*[tiab] AND cyclist*[tiab]) AND sport	63	
	Cerebral Palsy cycling[tiab] OR Cerebral Palsy cyclist*[tiab] NOT children	17	
	Tricycling[tiab] OR tricycle*[tiab] OR tribike*[tiab] OR tricyclist*[tiab] AND sport	34	
	Total	411	
Medline	Para-cycling OR paracycling OR (paralympic AND cycling) OR para-cyclist*OR (paralympic AND cyclist*)	49	
	handbike OR handcycle OR handcyclist* OR handcycling OR handbiking OR (“hand cycling”) OR (“hand cycle”) (8-7-2020)	140	
	(tandem AND cycling) OR (tandem AND bike*) OR (tandem AND bicycle*) OR (tandem AND cyclist*) AND sport	45	
	((Amputation AND cycling) OR (amputation AND cyclist*) OR (amputee AND cycling) OR (amputee AND cyclist*) OR (prostheses AND cycling) OR (prostheses AND cyclist*) OR (prosthesis AND cycling) OR (prosthesis AND cyclist*) OR (prosthetic AND cycling) OR (prosthetic AND cyclist*)) AND sport	219	
	((Cerebral AND Palsy AND cycling) OR (Cerebral AND Palsy AND cyclist)) AND sport	422	
	(Tricycling OR tricycle* OR tribike* OR tricyclist*) AND sport	724	

	Total	1599	
Scopus	Para-cycling OR paracycling OR (paralympic AND cycling) OR para-cyclist OR (paralympic AND cyclist)	130	
	handbike OR handcycle OR handcyclist* OR handcycling OR handbiking OR (“hand cycling”) OR (“hand cycle”) (8-7-2020)	338	
	((tandem AND cycling) OR (tandem AND bike) OR (tandem AND bicycle) OR (tandem AND cyclist)) AND sport	68	
	((Amputation AND cycling) OR (amputation AND cyclist) OR (amputee AND cycling) OR (amputee AND cyclist) OR (prostheses AND cycling) OR (prostheses AND cyclist*) OR (prosthesis AND cycling) OR (prosthesis AND cyclist) OR (prosthetic AND cycling) OR (prosthetic AND cyclist)) AND sport	339	
	((Cerebral AND Palsy AND cycling) OR (Cerebral AND Palsy AND cyclist)) AND sport NOT children	28	
	(Tricycling OR tricycle OR tribike OR tricyclist) AND sport	23	
	Total	926	
Total		3373	1116

References

References with asterisk * were part of the review

Abbiss, C. R., & Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Med, 38*(3), 239-252. https://doi.org/10.2165/00007256-200838030-00004

*Abel, T., Bonin, D., Albracht, K., Zeller, S., Brüggemann, G., & Burkett, B. (2010). Kinematic profile of the elite handcyclist. *Paper presented at the 28th International Conference on Biomechanics in Sports*.

*Abel, T., Burkett, B., Thees, B., Schneider, S., Askew, C. D., & Struder, H. K. (2015). Effect of three different grip angles on physiological parameters during laboratory handcycling test in able-bodied participants. *Frontiers in Physiology, 6*, 331. https://doi.org/10.3389/fphys.2015.00331

*Abel, T., Schneider, S., Platen, P., & Struder, H. K. (2006). Performance diagnostics in handbiking during competition. *Spinal Cord, 44*(4), 211-216. https://doi.org/10.1038/sj.sc.3101845

Alexander, L. A. J., Eken, M. M., Teoh, C. S., Stuart, M. C., Derman, E. W., & Blauwet, C. A. (2022). Patterns of athlete medication use at the 2018 Pyeongchang Paralympic Games: A descriptive cohort study. *American Journal of Physical Medicine and Rehabilitation, 101*(3), 270-278. https://doi.org/10.1097/phm.0000000000001751

*Alkemade, P., De Korte , J. Q., Bongers, C. C. W. G., Daanen, H. A. M., Hopman, M. T. E., Janssen, T. W. J., & Eijsvogels, T. M. H. (2023). Humid heat equally impairs maximal exercise performance in elite para-athletes and able-bodied athletes. *Medicine & Science in Sports & Exercise, 55*(10), 1835-1844. https://doi.org/10.1249/MSS.0000000000003222

Alves, E. d. S., dos Santos, R. V. T., de Lira, F. S., Almeida, A. A., Edwards, K., Benvenutti, M., Tufik, S., & De Mello, M. T. (2021). Effects of intensity-matched exercise at different intensities on inflammatory responses in able-bodied and spinal cord injured individuals. *The Journal of Spinal Cord Medicine, 44*(6), 920-930. https://doi.org/10.1080/10790268.2020.1752976

*Antunes, D., Borszcz, F. K., Nascimento, E. M. F., Cavalheiro, G. P., Fischer, G., Brickley, G., & de Lucas, R. D. (2022). Physiological and perceptual responses in spinal cord injury handcyclists during an endurance interval training: The role of critical speed. *American Journal of Physical Medicine and Rehabilitation, 101*(10), 977-982. https://doi.org/10.1097/PHM.0000000000001890

*Arnet, U., van Drongelen, S., Schlussel, M., Lay, V., van der Woude, L. H., & Veeger, H. E. (2014). The effect of crank position and backrest inclination on shoulder load and mechanical efficiency during handcycling. *Scandinavian Journal of Medicine and Science in Sports, 24*(2), 386-394. https://doi.org/10.1111/j.1600-0838.2012.01524.x
Bachar, D., & Douer, O. F. (2022). Sleep habits, quality and chronotype of paralympic athletes. *European Journal of Adapted Physical Activity, 15*, 3-3. https://doi.org/10.5507/euj.2021.014
*Barrat, P. (2011). Kinetics of sprint cycling with a below-knee prosthetic limb: A case study of a paralympic champion. *Portuguese Journal of Sport Sciences, 11 (Suppl. 2)*, 151-154.
*Baur, H., Stapelfeldt, B., Hirschmuller, A., Gollhofer, A., & Mayer, F. (2008). Functional benefits by sport specific orthoses in a female paralympic cyclist: A case report. *Foot and Ankle International, 29*(7), 746-751. https://doi.org/10.3113/FAI.2008.0746
*Belloli, M., Cheli, F., Bayati, I., Giappino, S., & Robustelli, F. (2014). Handbike aerodynamics: Wind tunnel versus track tests. *Procedia Engineering*, 72, 750-755 . https://doi.org/10.1016/j.proeng.2014.06.127
*Boer, P.-H., & Terblanche, E. (2014). Relationship between maximal exercise parameters and individual time trial performance in elite cyclists with physical disabilities. *South African Journal for Research in Sport, Physical Education and Recreation, 36*(1), 1-10. https://journals.co.za/content/sport/36/1/EJC151482
*Borg, D. N., Osborne, J. O., Tweedy, S. M., Liljedahl, J. B., & Nooijen, C. F. J. (2022). Bicycling and tricycling road race performance in international para-cycling events between 2011 and 2019. *American Journal of Physical Medicine and Rehabilitation, 101*(4), 384-388. https://doi.org/10.1097/PHM.0000000000001819
*Brickley, G., & Gregson, H. C. (2011). A case study of a paralympic cerebral palsy cyclist using torque analysis. *International Journal of Sports Science & Coaching, 6*(2), 269-272. https://doi.org/10.1260/1747-9541.6.2.269
*Burkett, B. J., & Mellifont, R. B. (2008). Sport science and coaching in paralympic cycling. *International Journal of Sports Science & Coaching, 3*(1), 95-103. https://search.ebscohost.com/login.aspx?direct=true&db=sph&AN=31637645&lang=nl&site=ehost-live
Chaikhot, D., Taylor, M. J. D., & Hettinga, F. J. (2018). Sex differences in wheelchair propulsion biomechanics and mechanical efficiency in novice young able-bodied adults. *European Journal of Sport Science, 18*(5), 650-658. https://doi.org/10.1080/17461391.2018.1447019
*Childers, W. L., Gallagher, T. P., Duncan, J. C., & Taylor, D. K. (2015). Modeling the effect of a prosthetic limb on 4-km pursuit performance. *International Journal of Sports Physiology and Performance, 10*(1), 3-10. https://doi.org/10.1123/ijspp.2013-0519
Childers, W. L., & Gregor, R. J. (2011). Effectiveness of force production in persons with unilateral transtibial amputation during cycling. *Prosthetics and Orthotics International, 35*(4), 373-378. https://doi.org/10.1177/0309364611423129
*Childers, W. L., Kistenberg, R. S., & Gregor, R. J. (2011). Pedaling asymmetries in cyclists with unilateral transtibial amputation: Effect of prosthetic foot stiffness. *Journal of Applied Biomechanics, 27*(4), 314-321. https://doi.org/10.1123/jab.27.4.314
*de Groot, S., Kouwijzer, I., Hoekstra, S. P., Vroemen, G., Valent, L. J. M., HandbikeBattle group, & van der Woude, L. H. V. (2023). External and internal work load during a mountain time trial in trained handcyclists versus a world-class handcyclist and determinants of performance. *American Journal of Physical Medicine and Rehabilitation, 102*(6), 550-559. https://doi.org/10.1097/PHM.0000000000002050
de Koning, J. J., Bobbert, M. F., & Foster, C. (1999). Determination of optimal pacing strategy in track cycling with an energy flow model. *Journal of Science and Medicine in Sport, 2*(3), 266-277. https://doi.org/10.1016/s1440-2440(99)80178-9
De Pauw, K., Roelands, B., Cheung, S. S., de Geus, B., Rietjens, G., & Meeusen, R. (2013). Guidelines to classify subject groups in sport-science research. *International Journal of Sports Physiology and Performance, 8*(2), 111-122. https://doi.org/10.1123/ijspp.8.2.111

Decroix, L., De Pauw, K., Foster, C., & Meeusen, R. (2016). Guidelines to classify female subject groups in sport-science research. *International Journal of Sports Physiology and Performance, 11*(2), 204-213. https://doi.org/10.1123/ijspp.2015-0153

Dyer, B. (2016). Cycling with an amputation: A systematic review. *Prosthetics and Orthotics International, 40*(5), 538-544. https://doi.org/10.1177/0309364615610659

*Dyer, B. (2018). The impact of lower-limb prosthetic limb use in international c4 track para-cycling. *Disability and Rehabilitation: Assistive Technology, 13*(8), 798-802. https://doi.org/10.1080/17483107.2017.1384074

*Dyer, B., & Disley, B. X. (2020). The aerodynamic impact of a range of prostheses designs when cycling with a trans-tibial amputation. *Disability and Rehabilitation: Assistive Technology, 15*(5), 577-581. https://doi.org/10.1080/17483107.2019.1594409

*Dyer, B., Glithro, R., & Batley, A. (2022a). The design of an upper arm prosthesis utilising 3d printing conceived for the 2020 Tokyo Paralympic Games: A technical note. *Journal of Rehabilitation and Assistive Technologies Engineering, 9*, 20556683221113309. https://doi.org/10.1177/20556683221113309

*Dyer, B., Gumowski, K., & Starczewski, M. (2022b). The aerodynamic assessment of tandem cyclists in preparation for the 2021 Paralympic Games: A case study. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*. https://doi.org/10.1177/17543371221100050

*Dyer, B., & Woolley, H. (2017). Development of a high-performance transtibial cycling-specific prosthesis for the London 2012 Paralympic Games. *Prosthetics and Orthotics International, 41*(5), 498-502. https://doi.org/10.1177/0309364616682386

Edwards, A., & Polman, R. (2012). *Pacing in sport and exercise: A psychophysiological perspective*. Nova Science.

*Englert, C., Havik, L., Zhang, Q., & Oudejans, R. (2018). Can you go the extra mile? The effect of ego depletion on endurance performance. *International journal of sport psychology, 49*, 505-520. https://doi.org/10.7352/IJSP.2018.49.505

Faria, E. W., Parker, D. L., & Faria, I. E. (2005a). The science of cycling: Factors affecting performance - part 2. *Sports Med, 35*(4), 313-337. https://doi.org/10.2165/00007256-200535040-00003

Faria, E. W., Parker, D. L., & Faria, I. E. (2005b). The science of cycling: Physiology and training - part 1. *Sports Med, 35*(4), 285-312. https://doi.org/10.2165/00007256-200535040-00002

*Fischer, G., Tarperi, C., George, K., & Ardigo, L. P. (2014). An exploratory study of respiratory muscle endurance training in high lesion level paraplegic handbike athletes. *Clinical Journal of Sport Medicine, 24*(1), 69-75. https://doi.org/10.1097/JSM.0000000000000003

*Flueck, J. L. (2020). Body composition in swiss elite wheelchair athletes. *Frontiers in Nutrition, 7*, 1. https://doi.org/10.3389/fnut.2020.00001

*Flueck, J. L., Gallo, A., Moelijker, N., Bogdanov, N., Bogdanova, A., & Perret, C. (2019). Influence of equimolar doses of beetroot juice and sodium nitrate on time trial performance in handcycling. *Nutrients, 11*(7). https://doi.org/10.3390/nu11071642

García-López, J., Rodríguez-Marroyo, J. A., Juneau, C. E., Peleteiro, J., Martínez, A. C., & Villa, J. G. (2008). Reference values and improvement of aerodynamic drag in professional cyclists. *Journal of Sports Sciences, 26*(3), 277-286. https://doi.org/10.1080/02640410701501697

*Goosey-Tolfrey, V. L., Alfano, H., & Fowler, N. (2008). The influence of crank length and cadence on mechanical efficiency in hand cycling. *European Journal of Applied Physiology, 102*(2), 189-194. https://doi.org/10.1007/s00421-007-0576-7

*Graham-Paulson, T., Perret, C., & Goosey-Tolfrey, V. (2016). Improvements in cycling but not handcycling 10 km time trial performance in habitual caffeine users. *Nutrients, 8*(7). https://doi.org/10.3390/nu8070393

*Graham-Paulson, T., Perret, C., & Goosey-Tolfrey, V. (2018). Case study: Dose response of caffeine on 20-km handcycling time trial performance in a paratriathlete. *International Journal of Sport Nutrition and Exercise Metabolism 28*(3), 274-278. https://doi.org/10.1123/ijsnem.2017-0089

*Groen, W. G., van der Woude, L. H., & De Koning, J. J. (2010). A power balance model for handcycling. *Disability and Rehabilitation: Assistive Technology, 32*(26), 2165-2171. https://doi.org/10.3109/09638288.2010.505677

Hettinga, F. J., de Koning, J. J., Hulleman, M., & Foster, C. (2012). Relative importance of pacing strategy and mean power output in 1500-m self-paced cycling. *British Journal of Sports Medicine, 46*(1), 30-35. https://doi.org/10.1136/bjsm.2009.064261

Hofmijster, M. J., Landman, E. H., Smith, R. M., & Van Soest, A. J. (2007). Effect of stroke rate on the distribution of net mechanical power in rowing. *Journal of Sports Sciences, 25*(4), 403-411. https://doi.org/10.1080/02640410600718046

Jeukendrup, A. E., Craig, N. P., & Hawley, J. A. (2000). The bioenergetics of world class cycling. *Journal of Science and Medicine in Sport, 3*(4), 414-433. https://doi.org/10.1016/s1440-2440(00)80008-0

Jeukendrup, A. E., & Martin, J. (2001). Improving cycling performance: How should we spend our time and money. *Sports Med, 31*(7), 559-569. https://doi.org/10.2165/00007256-200131070-00009

*Kennedy, A. B., Patil, N., & Trilk, J. L. (2018). 'Recover quicker, train harder, and increase flexibility': Massage therapy for elite paracyclists, a mixed-methods study. *BMJ Open Sport & Exercise Medicine, 4*(1), e000319. https://doi.org/10.1136/bmjsem-2017-000319

Keogh, J. W. (2011). Paralympic sport: An emerging area for research and consultancy in sports biomechanics. *Sports Biomechanics, 10*(3), 234-253. https://doi.org/10.1080/14763141.2011.592341

*Kim, S. H., An, H. J., Choi, J. H., & Kim, Y. Y. (2017). Effects of 2-week intermittent training in hypobaric hypoxia on the aerobic energy metabolism and performance of cycling athletes with disabilities. *Journal of Physical Therapy Science, 29*(6), 1116-1120. https://doi.org/10.1589/jpts.29.1116

Konings, M. J., & Hettinga, F. J. (2018). Pacing decision making in sport and the effects of interpersonal competition: A critical review. *Sports Med, 48*(8), 1829-1843. https://doi.org/10.1007/s40279-018-0937-x

*Kopacz, K., Fronczek-Wojciechowska, M., Galczynski, S., Prusaczyk, S., & Padula, G. (2016). An analysis of muscle tension in tandem track cyclists. *Antropomotoryka. Journal of Kinesiology and Exercise Sciences, 75*(26), 23-28.

*Kopacz, K., Fronczek-Wojciechowska, M., Kosielski, P., & Padula, G. (2014). Movement analysis in tandem track cyclist using video analysis. *Journal of Kinesiology and Exercise Sciences, 68*(24), 59-64.

*Koutny, D., Palousek, D., Stoklasek, P., Rosicky, J., Tepla, L., Prochazkova, M., Svoboda, Z., & Krejci, P. (2013). The biomechanics of cycling with a transtibial prosthesis: A case study of a professional cyclist. *International Journal of Medical, Health, Pharmaceutical and Biomedical Engineering, 7*(12), 812-817.

*Kouwijzer, I., Nooijen, C. F. J., van Breukelen, K., Janssen, T. W. J., & de Groot, S. (2018). Effects of push-off ability and handcycle type on handcycling performance in able-bodied participants. *Journal of Rehabilitation Medicine, 50*(6), 563-568. https://doi.org/10.2340/16501977-2343

Kraaijenbrink, C., Vegter, R., de Groot, S., Arnet, U., Valent, L., Verellen, J., van Breukelen, K., Hettinga, F., Perret, C., Abel, T., Goosey-Tolfrey, V., & van der Woude, L. (2021). Biophysical aspects of handcycling performance in rehabilitation, daily life and recreational sports; a narrative review. *Disability and Rehabilitation: Assistive Technology, 43*(24), 3461-3475. https://doi.org/10.1080/09638288.2020.1815872

*Kramer, C., Hilker, L., & Bohm, H. (2009a). Influence of crank length and crank width on maximal hand cycling power and cadence. *European Journal of Applied Physiology, 106*(5), 749-757. https://doi.org/10.1007/s00421-009-1062-1

*Kramer, C., Schneider, G., Bohm, H., Klopfer-Kramer, I., & Senner, V. (2009b). Effect of different handgrip angles on work distribution during hand cycling at submaximal power levels. *Ergonomics, 52*(10), 1276-1286. https://doi.org/10.1080/00140130902971916

*Leicht, C. A., Smith, P. M., Sharpe, G., Perret, C., & Goosey-Tolfrey, V. L. (2010). The effects of a respiratory warm-up on the physical capacity and ventilatory response in

paraplegic individuals. *European Journal of Applied Physiology, 110*(6), 1291-1298. https://doi.org/10.1007/s00421-010-1613-5
*Lepers, R., Stapley, P. J., & Knechtle, B. (2013). Analysis of marathon performances of disabled athletes. *Movement & Sport Sciences - Science & Motricité, 84*(84), 43-50. https://doi.org/10.1051/sm/2013078
*Liljedahl, J. B., Arndt, A., Nooijen, C. F., & Bjerkefors, A. (2023). Isometric, dynamic, and manual muscle strength measures and their association with cycling performance in elite paracyclists. *American Journal of Physical Medicine and Rehabilitation, 102*(5), 461-467. https://doi.org/10.1097/PHM.0000000000002014
*Liljedahl, J. B., Bjerkefors, A., Arndt, A., & Nooijen, C. F. J. (2021). Para-cycling race performance in different sport classes. *Disability and Rehabilitation: Assistive Technology, 43*(24), 3440-3444. https://doi.org/10.1080/09638288.2020.1734106
*Lima, G. B., Kons, R. L., Detanico, D., & Fischer, G. (2021). Time-trial performance of para-cycling athletes with visual impairment in tandem competitions: A retrospective analysis of 20 years. *American Journal of Physical Medicine & Rehabilitation*.
Lin, H., Tong, T. K., Huang, C., Nie, J., Lu, K., & Quach, B. (2007). Specific inspiratory muscle warm-up enhances badminton footwork performance. *Applied Physiology, Nutrition, and Metabolism, 32*(6), 1082-1088. https://doi.org/10.1139/H07-077
*Litzenberger, S., Mally, F., & Sabo, A. (2016). Biomechanics of elite recumbent handcycling: A case study. *Sports Engineering, 19*(3), 201-211. https://doi.org/10.1007/s12283-016-0206-x
*Lovell, D., Shields, D., Beck, B., Cuneo, R., & McLellan, C. (2012). The aerobic performance of trained and untrained handcyclists with spinal cord injury. *European Journal of Applied Physiology, 112*(9), 3431-3437. https://doi.org/10.1007/s00421-012-2324-x
Madden, R. F., Shearer, J., & Parnell, J. A. (2017). Evaluation of dietary intakes and supplement use in paralympic athletes. *Nutrients, 9*(11), 1266. https://doi.org/10.3390/nu9111266
Malizia, F., & Blocken, B. (2020). Bicycle aerodynamics: History, state-of-the-art and future perspectives. *Journal of Wind Engineering and Industrial Aerodynamics, 200*, 104134. https://doi.org/10.1016/j.jweia.2020.104134
*Malwina, K. A., Krzysztof, M., & Piotr, Z. (2015). Visual impairment does not limit training effects in development of aerobic and anaerobic capacity in tandem cyclists. *Journal of Human Kinetics, 48*(1), 87-97. https://doi.org/10.1515/hukin-2015-0095
*Mannion, P., Toparlar, Y., Blocken, B., Clifford, E., Andrianne, T., & Hajdukiewicz, M. (2018a). Aerodynamic drag in competitive tandem para-cycling: Road race versus time-trial positions. *Journal of Wind Engineering and Industrial Aerodynamics, 179*, 92-101. https://doi.org/10.1016/j.jweia.2018.05.011
*Mannion, P., Toparlar, Y., Blocken, B., Clifford, E., Andrianne, T., & Hajdukiewicz, M. (2018b). Analysis of crosswind aerodynamics for competitive hand-cycling. *Journal of Wind Engineering and Industrial Aerodynamics, 180*, 182-190. https://doi.org/10.1016/j.jweia.2018.08.002
*Mannion, P., Toparlar, Y., Blocken, B., Hajdukiewicz, M., Andrianne, T., & Clifford, E. (2019a). Computational fluid dynamics analysis of hand-cycle aerodynamics with static wheels: Sensitivity analyses and impact of wheel selection. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 235*(4), 286-300. https://doi.org/10.1177/1754337119853485
*Mannion, P., Toparlar, Y., Blocken, B., Hajdukiewicz, M., Andrianne, T., & Clifford, E. (2019b). Impact of pilot and stoker torso angles in tandem para-cycling aerodynamics. *Sports Engineering, 22*(1), 1-1. https://doi.org/10.1007/s12283-019-0301-x
*Mannion, P., Toparlar, Y., Clifford, E., Hajdukiewicz, M., Andrianne, T., & Blocken, B. (2019c). The impact of arm-crank position on the drag of a paralympic hand-cyclist. *Computer Methods in Biomechanics and Biomedical Engineering, 22*(4), 386-395. https://doi.org/10.1080/10255842.2018.1558217
*Mannion, P., Toparlar, Y., Clifford, E., Hajdukiewicz, M., Andrianne, T., & Blocken, B. (2019d). On the effects of crosswinds in tandem aerodynamics:An experimental and

computational study. *European Journal of Mechanics - B/Fluids, 74*, 68-80. https://doi.org/10.1016/j.euromechflu.2018.11.001

*Mannion, P., Toparlar, Y., Hajdukiewicz, M., Clifford, E., Andrianne, T., & Blocken, B. (2019e). Aerodynamics analysis of wheel configurations in paralympic hand-cycling: A computational study. *European Journal of Mechanics - B/Fluids, 76*, 50-65. https://doi.org/10.1016/j.euromechflu.2019.01.011

*Mason, B. S., Stone, B., Warner, M. B., & Goosey-Tolfrey, V. L. (2021). Crank length alters kinematics and kinetics, yet not the economy of recumbent handcyclists at constant handgrip speeds. *Scandinavian Journal of Medicine and Science in Sports, 31*(2), 388-397. https://doi.org/10.1111/sms.13859

*Mazzola, M., Andreoni, G., Campanardi, G., Costa, F., Gibertini, G., Grassi, D., & Romero, M. (2012). Effects of seat and handgrips adjustments on a hand bike vehicle. An ergonomic and aerodynamic study for a quantitative assessment of paralympics athlete's performance. In *Advances in usability evaluation part i* (pp. 569-576). https://www.scopus.com/inward/record.uri?eid=2-s2.0-85055946464&partnerID=40&md5=77b4d34c162edbe8ea46881ef672a97e

*Menaspa, P., Rampinini, E., Tonetti, L., & Bosio, A. (2012). Physical fitness and performances of an amputee cycling world champion: A case study. *International Journal of Sports Physiology and Performance, 7*(3), 290-294. https://doi.org/10.1123/ijspp.7.3.290

Messias, L. H. D., dos Reis, I. G. M., Ferrari, H. G., & de Barros Manchado-Gobatto, F. (2017). Physiological, psychological and biomechanical parameters applied in canoe slalom training: A review. *International Journal of Performance Analysis in Sport, 14*(1), 24-41. https://doi.org/10.1080/24748668.2014.11868700

Mohammadi-Abdar, H., Ridgel, A. L., Discenzo, F. D., & Loparo, K. A. (2014). Modeling and simulation of power sharing and interaction between riders on a tandem bicycle. *53rd IEEE Conference on Decision and Control*, Los Angeles, CA, USA, 2014, 6813-6817, https://doi: 10.1109/CDC.2014.7040459

Morrien, F., Taylor, M. J. D., & Hettinga, F. J. (2017). Biomechanics in Paralympics: Implications for performance. *International Journal of Sports Physiology and Performance, 12*(5), 578-589. https://doi.org/10.1123/ijspp.2016-0199

*Muchaxo, R., De Groot, S., Kouwijzer, I., Van Der Woude, L., Janssen, T., & Nooijen, C. F. J. (2021). A role for trunk function in elite recumbent handcycling performance? *Journal of Sports Science, 39*(20), 2312-2321. https://doi.org/10.1080/02640414.2021.1930684

*Muchaxo, R. E. A., de Groot, S., Kouwijzer, I., van der Woude, L. H. V., Nooijen, C. F. J., & Janssen, T. W. J. (2022). Association between upper-limb isometric strength and handcycling performance in elite athletes. *Sports Biomechanics*, 1-20. https://doi.org/10.1080/14763141.2022.2071760

*Muchaxo, R. E. A., de Groot, S., van der Woude, L. H. V., Janssen, T. W. J., & Nooijen, C. (2020). Do handcycling time-trial velocities achieved by para-cycling athletes vary across handcycling classes? *Adapted Physical Activity Quarterly, 37*(4), 461-480. https://doi.org/10.1123/apaq.2019-0143

*Muchaxo, R. E. A., Kouwijzer, I., van der Woude, L. H. V., Janssen, T. W. J., Nooijen, C. F. J., & de Groot, S. (2023). The impact of lower-limb function on upper-limb pull and push strength in elite handcycling athletes. *Sports Biomechanics*, 1-15. https://doi.org/10.1080/14763141.2023.2242323

Nevin, J., Kouwijzer, I., Stone, B., Quittmann, O. J., Hettinga, F., Abel, T., & Smith, P. M. (2022). The science of handcycling: A narrative review. *International Journal of Sports Physiology and Performance, 17*(3), 335-342. https://doi.org/10.1123/ijspp.2021-0458

Nevin, J., & Smith, P. (2021a). The effectiveness of a 30-week concurrent strength and endurance training program in preparation for an ultra-endurance handcycling challenge: A case study. *International Journal of Sports Physiology and Performance, 16*(11), 1712-1718. https://doi.org/10.1123/ijspp.2020-0749

*Nevin, J., Smith, P., Waldron, M., Patterson, S., Price, M., Hunt, A., & Blagrove, R. (2018). Efficacy of an 8-week concurrent strength and endurance training program on hand cycling performance. *Journal of Strength and Conditioning Research, 32*(7), 1861-1868. https://doi.org/10.1519/JSC.0000000000002569

*Nevin, J., & Smith, P. M. (2021b). The relationship between absolute and relative upper-body strength and handcycling performance capabilities. *International Journal of Sports Physiology and Performance, 16*(9), 1311-1318. https://doi.org/10.1123/ijspp.2020-0580

*Nooijen, C. F. J., Muchaxo, R., Liljedahl, J., Bjerkefors, A., Janssen, T., van der Woude, L., Arndt, A., & de Groot, S. (2021). The relation between sprint power and road time trial performance in elite para-cyclists. *Journal of Science & Medicine in Sport, 24*(11), 1193-1198. https://doi.org/10.1016/j.jsams.2021.04.014

Ouzzani, M., Hammady, H., Fedorowicz, Z., & Elmagarmid, A. (2016). Rayyan-a web and mobile app for systematic reviews. *Systematic Reviews, 5*(1), 210. https://doi.org/10.1186/s13643-016-0384-4

*Park, H. Y., Jung, W. S., Kim, J., Hwang, H., Kim, S. W., An, Y., Lee, H., Jeon, S., & Lim, K. (2020). Effects of 2-week exercise training in hypobaric hypoxic conditions on exercise performance and immune function in Korean national cycling athletes with disabilities: A case report. *International Journal of Environmental Research and Public Health, 17*(3). https://doi.org/10.3390/ijerph17030861

Perret, C. (2017). Elite-adapted wheelchair sports performance: A systematic review. *Disabil Rehabil, 39*(2), 164-172. https://doi.org/10.3109/09638288.2015.1095951

Perret, C., & Abel, T. (2016). Physiology. In Y. Vanlandewijck & W. Thompson (Eds.), *Training and coaching the paralympic athlete* (pp. 53-74). International Olympic Committee. https://doi.org/10.1002/9781119045144.ch3

Phillips, K. E., & Hopkins, W. G. (2020). Determinants of cycling performance: A review of the dimensions and features regulating performance in elite cycling competitions. *Sports Med Open, 6*(1), 23, Article Unsp 23. https://doi.org/10.1186/s40798-020-00252-z

*Riel, L. P., Adam-Cote, J., Daviault, S., Salois, C., Laplante-Laberge, J., & Plante, J. S. (2009). Design and development of a new right arm prosthetic kit for a racing cyclist. *Prosthetics and Orthotics International, 33*(3), 284-291. https://doi.org/10.1080/03093640903045198

*Runciman, P., Derman, W., Ferreira, S., Albertus-Kajee, Y., & Tucker, R. (2015). A descriptive comparison of sprint cycling performance and neuromuscular characteristics in able-bodied athletes and paralympic athletes with cerebral palsy. *American Journal of Physical Medicine and Rehabilitation, 94*(1), 28-37. https://doi.org/10.1097/PHM.0000000000000136

*Sanders, D., Spindler, D. J., & Stanley, J. (2022). The multidisciplinary physical preparation of a multiple paralympic medal-winning cyclist. *International Journal of Sports Physiology and Performance, 17*(8), 1316-1322. https://doi.org/10.1123/ijspp.2022-0039

Scaramella, J., Kirihennedige, N., & Broad, E. (2018). Key nutritional strategies to optimize performance in para athletes. *Physical Medicine and Rehabilitation Clinics of North America, 29*(2), 283-298. https://doi.org/10.1016/j.pmr.2018.01.005

Schoenmakers, P., Reed, K., Van Der Woude, L., & Hettinga, F. J. (2016). High intensity interval training in handcycling: The effects of a 7 week training intervention in able-bodied men. *Frontiers in Physiology, 7*, 638. https://doi.org/10.3389/fphys.2016.00638

*Seo, K., & Eda, S. (2018). The influence of the phase difference between the crank angle of the pilot and that of the stoker on the drag acting on a tandem bike. *Proceedings*, 2(6), 209. https://doi.org/10.3390/proceedings2060209

Shen, J. G., Brooks, M. B., Cincotta, J., & Manjourides, J. D. (2019). Establishing a relationship between the effect of caffeine and duration of endurance athletic time trial events: A systematic review and meta-analysis. *Journal of Science & Medicine in Sport, 22*(2), 232-238. https://doi.org/10.1016/j.jsams.2018.07.022

Smits, B. L., Pepping, G. J., & Hettinga, F. J. (2014). Pacing and decision making in sport and exercise: The roles of perception and action in the regulation of exercise intensity. *Sports Med, 44*(6), 763-775. https://doi.org/10.1007/s40279-014-0163-0

*Solazzi, L., Schinetti, G., & Adamini, R. (2022). Developed an innovative handbike fork made of composite material. *Studies in Health Technology and Informatics, 297*, 359-366. https://doi.org/10.3233/SHTI220861

Stephenson, B. T., Stone, B., Mason, B. S., & Goosey-Tolfrey, V. L. (2021). Physiology of handcycling: A current sports perspective. *Scandinavian Journal of Medicine and Science in Sports, 31*(1), 4-20. https://doi.org/10.1111/sms.13835

*Stone, B., Mason, B. S., Bundon, A., & Goosey-Tolfrey, V. L. (2019a). Elite handcycling: A qualitative analysis of recumbent handbike configuration for optimal sports performance. *Ergonomics, 62*(3), 449-458. https://doi.org/10.1080/00140139.2018.1531149

*Stone, B., Mason, B. S., Warner, M. B., & Goosey-Tolfrey, V. L. (2019b). Horizontal crank position affects economy and upper limb kinematics of recumbent handcyclists. *Medicine and Science in Sports and Exercise, 51*(11), 2265-2273. https://doi.org/10.1249/MSS.0000000000002062

*Stone, B., Mason, B. S., Warner, M. B., & Goosey-Tolfrey, V. L. (2019c). Shoulder and thorax kinematics contribute to increased power output of competitive handcyclists. *Scandinavian Journal of Medicine and Science in Sports, 29*(6), 843-853. https://doi.org/10.1111/sms.13402

Theisen, D. (2012). Cardiovascular determinants of exercise capacity in the paralympic athlete with spinal cord injury. *Experimental Physiology, 97*(3), 319-324. https://doi.org/10.1113/expphysiol.2011.063016

Tricco A.C., Lillie E., Zarin W., O'Brien K.K., Colquhoun H., Levac D., Moher D., Peters M.D.J., Horsley T., Weeks L., Hempel S., Akl E.A., Chang C., McGowan J., Stewart L., Hartling L., Aldcroft A., Wilson M.G., Garritty C., Lewin S., Godfrey C.M., Macdonald M.T., Langlois E.V., Soares-Weiser K., Moriarty J., Clifford T., Tunçalp Ö., & Straus S.E. (2018). Prisma extension for scoping reviews (prisma-scr): Checklist and explanation. *Annals of Internal Medicine, 169*(7), 467-473. https://doi.org/10.7326/M18-0850

Tweedy, S. M., Beckman, E. M., & Connick, M. J. (2014). Paralympic classification: Conceptual basis, current methods, and research update. *Paralympic Sports Medicine and Science, 6*(8 Suppl), S11-17. https://doi.org/10.1016/j.pmrj.2014.04.013

Tweedy, S. M., Mann, D., & Vanlandewijck, Y. C. (2016). Research needs for the development of evidence-based systems of classification for physical, vision, and intellectual impairments. In *Training and coaching the paralympic athlete* (pp. 122-149). https://doi.org/10.1002/9781119045144.ch7

Tweedy, S. M., & Vanlandewijck, Y. C. (2011). International paralympic committee position stand--background and scientific principles of classification in paralympic sport. *British Journal of Sports Medicine, 45*(4), 259-269. https://doi.org/10.1136/bjsm.2009.065060

Union Cycliste Internationale, UCI cycling regulations, 12 (2020). https://www.uci.org/docs/default-source/rules-and-regulations/16-par-20200211-e.pdf

Van Biesen, D., Hettinga, F. J., McCulloch, K., & Vanlandewijck, Y. (2016). Pacing profiles in competitive track races: Regulation of exercise intensity is related to cognitive ability. *Frontiers in Physiology, 7*, 624. https://doi.org/10.3389/fphys.2016.00624

van der Woude, L. H., Veeger, H. E., Dallmeijer, A. J., Janssen, T. W., & Rozendaal, L. A. (2001). Biomechanics and physiology in active manual wheelchair propulsion. *Medical Engineering & Physics, 23*(10), 713-733. https://doi.org/10.1016/s1350-4533(01)00083-2

van Ingen Schenau, G. J., & Cavanagh, P. R. (1990). Power equations in endurance sports. *Journal of Biomechanics, 23*(9), 865-881. https://doi.org/10.1016/0021-9290(90)90352-4

*Vegter, R. J. K., Mason, B. S., Sporrel, B., Stone, B., van der Woude, L. H. V., & Goosey-Tolfrey, V. L. (2019). Crank fore-aft position alters the distribution of work over the push and pull phase during synchronous recumbent handcycling of able-bodied participants. *PLoS ONE, 14*(8), e0220943. https://doi.org/10.1371/journal.pone.0220943

*Watanabe, K., Yamaguchi, Y., Fukuda, W., Nakazawa, S., Kenjo, T., & Nishiyama, T. (2020). Neuromuscular activation pattern of lower extremity muscles during pedaling in cyclists with single amputation of leg and with two legs: A case study. *BMC Research Notes, 13*(1), 299. https://doi.org/10.1186/s13104-020-05144-9

*West, C. R., Gee, C. M., Voss, C., Hubli, M., Currie, K. D., Schmid, J., & Krassioukov, A. V. (2015). Cardiovascular control, autonomic function, and elite endurance performance in spinal cord injury. *Scandinavian Journal of Medicine and Science in Sports, 25*(4), 476-485. https://doi.org/10.1111/sms.12308

*Wright, R. L. (2015). Positive pacing strategies are utilized by elite male and female para-cyclists in short time trials in the velodrome. *Frontiers in Physiology, 6*, 425. https://doi.org/10.3389/fphys.2015.00425

*Zeller, S., Abel, T., Smith, P. M., & Strueder, H. K. (2015). Influence of noncircular chainring on male physiological parameters in hand cycling. *Journal of Rehabilitation Research & Development, 52*(2), 211-220. https://doi.org/10.1682/JRRD.2014.03.0070

*Zeller, S., Abel, T., & Strueder, H. K. (2017). Monitoring training load in handcycling: A case study. *Journal of Strength and Conditioning Research, 31*(11), 3094-3100. https://doi.org/10.1519/JSC.0000000000001786

Zhao, K., Hohmann, A., Chang, Y., Zhang, B., Pion, J., & Gao, B. (2019). Physiological, anthropometric, and motor characteristics of elite Chinese youth athletes from six different sports. *Frontiers in Physiology, 10*. https://doi.org/10.3389/fphys.2019.00405